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RELIABILITY DATA COLLECTION IN MAINTENANCE SERVICE PROVIDER ORGANIZATION

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Abstract of master's thesis

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Abstract

Planning and assessing the effectiveness of maintenance operations relies heavily on the reliability data of the examined equipment. This data is readily available for equipment owners, but maintenance service providers struggle with acquiring it in quantity and quality needed for comprehensive analysis. Collecting this data would offer significant possibilities to develop both physical and service products for an original equipment manufacturer that also provides maintenance services for its equipment.

In this thesis, a method for constructing and implementing a reliability data collection system is developed. During the thesis work, the current state of reliability data collection in the subject company was assessed, available data sources were identified, appropriate analysis tools were chosen, and data collection method and reporting models structured. The thesis is based on literacy research on the topic and interviews of subject company employees.

The constructed method provides an iterative process that initially produces a reporting structure based on qualitative analysis of the product. When adequate amount of reliability data is collected, iteration round provides the organization with maintenance recommendations based on quantitative analysis. Analysis tools used in the process are well established and standardised by international standardization organizations.

Keywords Reliability, data collection, services, maintenance

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Tiivistelmä

Huoltotoimintojen suunnittelu ja tehokkuuden arviointi nojaa vahvasti tutkittavasta laitteistosta kerättyyn vikaantumis- ja luotettavuusdataan. Tämä tieto on laitteistojen omistajille helposti saatavilla, mutta huoltopalveluiden toimittajille sen kerääminen analyysien vaatimassa laajuudessa on haasteellista. luotettavuusdatan kerääminen tarjoaa laitteiden ja palveluiden toimittajalle merkittäviä mahdollisuuksia sekä laitteiden että palveluiden tuotekehityksessä.

Tässä diplomityössä esitellään luotettavuusdatan keräämisjärjestelmän muodostamiseen ja käyttöönottoon tarkoitetun metodin kehitys. Diplomityön aikana määritettiin datankeräyksen tämänhetkinen tila kohde yrityksessä, tunnistettiin mahdolliset datalähteet, sopivat analysointimenetelmät valittiin ja mallit tiedonkeruuprosessiksi ja raportointi malleiksi kehitettiin. Diplomityö perustuu kirjallisuustutkimukseen ja kohdeyhtiön työntekijöiden haastatteluihin.

Muodostettu metodi tarjoaa iteratiivisen prosessin joka tuottaa aluksi kvalitatiiviseen systeemianalyysiin perustuvan raportointi rakenteen. Kun luotettavuusdataan on kerätty tarvittava määrä, seuraava iteraatiokierros tuottaa kvantitatiiviseen analyysiin perustuvan huoltosuosituksen. Prosessissa käytetyt analysointi menetelmät ovat hyvin tunnettuja ja ne on standardoitu kansainvälisten standardointiorganisaatioiden toimesta.

Avainsanat Luotettavuus, tiedon kerääminen, palvelut, huoltopalvelut

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1 Introduction

Planning and assessing the performance of a maintenance operation relies heavily on data collected about the subject equipment and carried out operations. In traditional production organizations that own and maintain the production equipment, collecting and utilizing this data has long been a standard procedure as the data has been readily available within the organization.

During the past two decades, equipment manufacturers have been moving toward offering maintenance services to the users of their equipment. In addition to maintenance planning and performance assessing the reliability data is additionally important for both physical and service product development purposes for the OEM service providers. However, obtaining quality data from the customer interface is not as easy as it for the in-house maintenance organizations.

Scientific research on reliability data collection and analysis is readily available as there has been a great need to develop maintenance programs ever since the beginning of the 20^{th} century. However, this research has been concentrating on maintenance carried out by the equipment owner. The OEM service provider view point is still so new that research validating the need and practices for data collection have only been conducted recently.

Service providers can use the maintenance and reliability data collected from their installed base for example to assess and analyse the reliability, availability and maintainability of different products, to develop maintenance recommendations provided with products and to produce life cycle cost estimations to be used as marketing and proof of concept tools.

Utilizing effective data collection from the installed base can additionally offer the service provider a better understanding about the reliability and availability aspects of a product than what a single in-house maintenance organization can possess. This is possible due to larger amount of equipment individuals and for example the wider pool of operational conditions and applications available for examination.

This thesis is written for a Finnish OEM and service provider company Outotec. The company has a long history on equipment, process and technology deliveries in minerals processing and metallurgical industries. For the past half decade the company has been developing its ability to provider maintenance services for its customers.

As the service operations of the company are still finding their form, one of the development areas is information collection and utilization. The organization is facing challenges with both local data collection and global data utilization.

This thesis aims to provide solutions to problems the subject company is facing by identifying available information sources, assessing their usability, developing a process for data collection, and giving requirements for collected data and suggestions on additional ways to utilize the collected data.

The work reported in this thesis was conducted in three phases. In the first phase, the available information sources and information gathering procedures currently used were identified by interviewing company employees (interviewees listen in Appendix 1). In the second stage the author got himself familiar with available reliability, availability and life cycle cost analysis tools and their data needs by using literary sources and information acquired from the interviews conducted in the first phase. On the third phase, the results of the previous phases were utilized in developing a data collection method that takes into account the previously described challenges.

The work concentrated on technologies under service product management organization located in Finland. This group of equipment included the following products: flotation machines, filters, hydrometallurgical equipment, and equipment related to flash smelting and ferrous smelting technologies. Due to large variance on mechanical complexities of covered products, the developed information collection process and reporting requirements remain rather generic as they are supposed to be applicable on all technologies.

This thesis is structured as follows: Chapter 2 introduces the basic concepts related to maintenance operations. In the chapter 3 installed base information as a service development tool is introduced. Chapter 4 describes the developed data collection process, chapter 5 describes the analysis tools utilized and their data needs and chapter 6 discusses factors affecting data quality. In chapter 7 list of available data sources is provided and their usability discussed. Chapter 8 describes the selection and development of report types and data classification. Chapter 9 briefly discusses possible ways to further utilize the collected data. Final conclusions are presented on Chapter 10.

2 Maintenance

This chapter introduces key maintenance concepts and terms that are needed to understand the content of this thesis. The chapter is mostly based on standard EN 13306 which specifies the generic terms and definitions of maintenance. Other sources are indicated in the text.

Maintenance is defined as the combination of technical, administrative and managerial actions during the life cycle of an item to retain it in, or restore it to, a state where it can perform the required function. In other words, maintenance covers all actions carried out to enssure that a system or equipment can perform its designed operation.

Maintained items can be parts, components, devices, subsystems, functional units, equipment or systems that can be individually described and considered as an entity. Items can be classified as repairable items that can be restored to the functional state after a fault, consumable items that are expendable and are changed if broken, and spare parts that are intended to be replaced a corresponding item to retain or maintain the original required function of the original item. The main difference between a consumable item and a spare part is that spare parts are typically the place and type specific (e.g. bearings) whereas consumables are more generic (e.g. rubber seals, sealing material).

Maintenance is divided into several different types. In the context of this thesis, most important types are corrective maintenance, preventive maintenance, predetermined maintenance, condition based maintenance, predictive maintenance and scheduled maintenance. These maintenance type definitions are overlapping as can be seen in the following descriptions.

Corrective maintenance is carried out after a fault and intends to restore the item to the functional state.

Preventive maintenance aims to reduce the probability of a failure or degradation of the functioning of an item. It is carried out at predetermined intervals or according to prescribed criteria.

Predetermined maintenance is a form of preventive maintenance that is carried out at the established intervals of time or units of use, but without previous condition investigation.

Condition based maintenance is carried out according to criteria set on item performance. The condition can be determined by using condition inspection routines or by condition monitoring equipment used during item operation.

Predictive maintenance is carried out following a forecast derived from the analysis or known characteristics and evaluation of the significant parameters of degradation of the item.

Scheduled maintenance is carried out according to an established time schedule or established the number of units of use.

2.1 Failures

Maintained items are subject to failures. Failure is an event that causes the item to loss its ability to perform the required function. After a failure, the item is in a fault state. It is important to understand the difference between these two terms; a failure is an event, a fault is a state.

In maintenance point of view, failures are the subject of interest. There are several different ways to classify failures. Two commonly used divisions are safe/unsafe and detected/undetected. In the first one, safe failures do not cause a harm or hazard to personnel, environment, equipment or production, whereas unsafe failures do. On the latter, detected failures are ones which can be observed when they occur whereas undetected failures are not observed when they take place but later in time (Gruhn & Cheddie, 2006). An Example of a detected failure would be a light bulb burning out in an occupied room. In contrast, a light bulb located in a rarely used storage room burning out at the moment it is turned off and observed to be broken only when someone tries to turn the light on the next time. As these simplified examples show, the classification of a failure is not dependent only on the type of the equipment but also its use and the way and time the failure occurs. Detected and undetected failures are also be called evident and hidden failures, respectively.

The different ways an item can fail are called failure modes. An item can have several different failure modes. As complexity increases, so does the number of possible failure modes. For example, a machine consisting of multiple parts can experience a failure when any of its components fail. Therefore each failure mode of the machine is caused by some failure mode of some of its components. Of course there can also be such component failure modes that do not cause the machine itself to fail.

Each failure mode has a failure cause, a circumstance in the specification, design, manufacture, installation, use or maintenance that results in the failure. Causes can have complex relations where the observed cause arises from one or more other causes. In these kinds of cases, the initial stimulus that starts the consequence chain finally leading to the failure is called a root cause. If a single cause results in multiple failures, these failures are classified as common cause failures.

Failures actuate through a failure mechanism, a physical, chemical or other process which leads up to the failure.

Finally, each failure has an effect, a way it affects the performance or operation of the item and further the larger system the item is part of.

2.2 System states

As described earlier, failures are events that render the item from an operational state to a fault state. In addition to these two, there are additional terms used to describe the state the item is in.

The state of an item can be observed from two perspectives: the state the item should be in and the state the item actually is in. For the supposed state, terms “required state” and “non-required state” are used. In the required state the item should have the ability to perform its functions. In the non-required state there is no perquisite for the state the item is in. On the other hand, the actual state of the item is described using terms “up state” and “down state”. In the up state the item has the ability to perform its functions and in the down state it does not. For the time an item is in any state, a corresponding time term can be used. So, for example, the time used in the up state is called up time and the time item should be functioning is called required time.

When an item is in the up state, it can be in an operational state; performing the required function, in an idle state; not operating during non-required time, or in a standby state; not operating during required time. In other words an item in the standby state is required to be functional but not operating, while an idle item is not required to be in functional condition.

Figure 1: Times and item states. illustrates corresponding times.

2.3 Metrics

Terms introduced above describe qualitative characteristics of failures. For quantitative analysis of failures to be possible, metrics representing failure occurrence rates and frequencies are needed. The most commonly used ones are the failure rate (λ), mean time between failures (MTBF) and mean time to failure (MTTF).

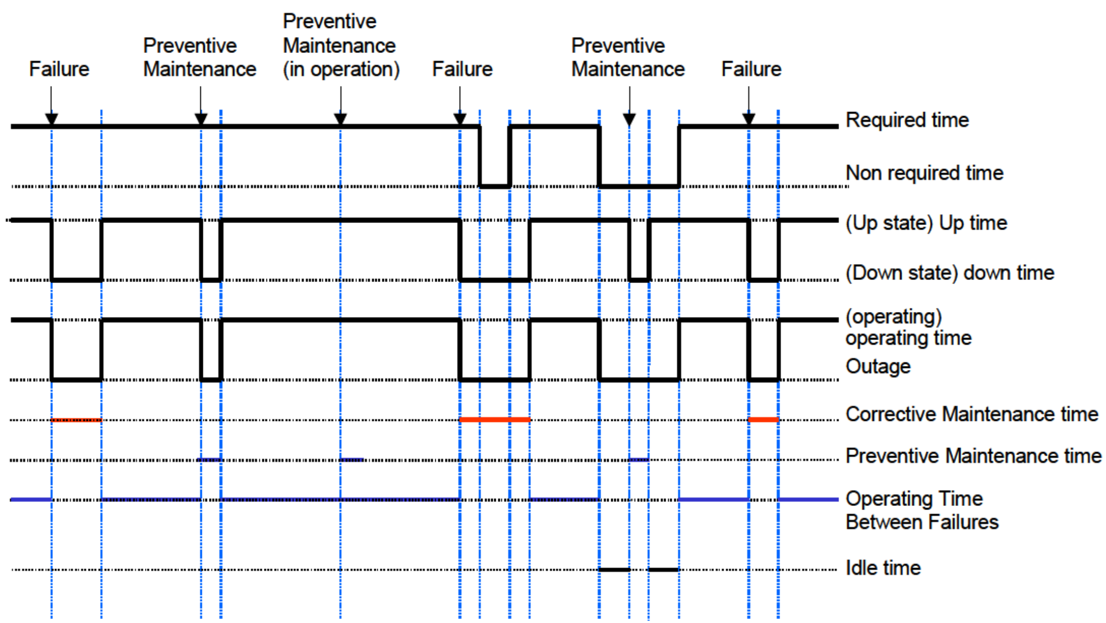


Figure 1: Times and item states. (SFS-EN 13306, 2010)

A brief summary on the metrics based on Smith (2011) and Berk (2009) is provided below. Deeper explanations can be found on textbooks on maintenance and reliability engineering.

Failure rate measures the amount of failures in observed time. Typically expressed as the observed failure rate and defined as the ratio of the total number of failures to the total cumulative observed time. If there are N items of which k have failed in the observed time T, the observed λ is:

$$\hat{\lambda} = \frac{k}{T} \tag{1}$$

Typical unit used to present failure rates is 1 / 10^6 hours.

It is important to notice that this is an estimate of the failure rate and that the absolute failure rate is revealed only after all of the N items have failed. Similarly it has to be noted that this value is an average over a period of time and does not by itself indicate if the rate is increasing, constant or decreasing. Therefore in analytical context the failure rate is a meaningful parameter only when it can be presumed to be constant.

Mean time between failures, MTBF, is used for repairable items. It presents the average time interval between failures occurring to the item. It is computed as the ratio of total cumulative observed time for the total number of failures. For N items, the observed MTBF is presented as:

$$\hat{\theta} = \frac{T}{k} \tag{2}$$

Like the failure rate, MTBF is an average and same remarks apply. When comparing λ and θ, relation $\theta = 1/\lambda$ can be noticed. However, this only applies if λ is constant.

Mean time to failure, MTTF, is a similar metric as MTBF, but it is used to replaceable items. Therefore it is counted as average life time of N items:

$$\hat{\theta} = \frac{T_{life-time}}{N} \tag{3}$$

Once again, same remarks apply; λ is presumed to be constant.

When discussing the performance of items; especially larger, more complex systems; these item metrics are typically not most suitable ones to use. Reliability and availability are item or system properties used to measure performance and to compare different systems.

Reliability presents the ability of an item to perform required function under given conditions for a given time. Reliability is typically presented as a probability that the item will perform its intended function. According to Smith (2011), item reliability can be calculated using the failure rate:

$$R(t) = e^{-\lambda t} \tag{4}$$

When λt is small (< 0.1), $e^{-\lambda t}$ approaches $(1 - \lambda t)$. Therefore the probability of failure $(1 – R(t))$ approximates to λt. This can lead to a situation where failure rate and probability of failure have the same numerical value making them appear as the same thing. However, the failure rate has a unit (events per time) whereas failure probability is dimensionless. Additionally statistical distribution has to be considered when discussing failure probabilities.

Availability represents the ability of the item to be in a state to perform as and when required. Availability is typically presented as a percentage of time the item is in tha available state of its life time or examination time.

To facilitate analysis, Smith (2011) defines availability as “a parameter that describes the proportion of time for which an item is not in a failed state.” Analogously unavailability (1-availability) is the proportion of time for which an item is in a fault state. Typically, it is more suitable for defining the unavailability of equipment as it can directly be used for example to calculate the costs of non-production time. To be able to define the unavailability of equipment, it is needed to understand mean down time (MDT).

MDT is average amount of time the equipment is out of operation due to a fault. MDT is not to be confused with mean time to repair (MTTR), which is the average time needed for the maintenance activity to repair the failure. MDT and MTTR are overlapping time periods and include the same activities but downtime begins with failure realization activity which is not included in the repair time. Similarly repair time includes post-replacement checks and alignment activities that can take place after the equipment has been returned to operational state and therefore are not included in downtime.

Important aspect to remember about down times is that they vary and usually are distributed following a logarithmical normal distribution.

Unavailability can be calculated using MTBF and MDT:

$$Un = \frac{MDT}{MTBF+MDT} \tag{5}$$

Multiplying by failure rate:

$$Un = \frac{\lambda MDT}{1+\lambda MDT} \tag{5}$$

As λ, MDT is typically small (<0.1), previous can be written as:

$$Un \cong \lambda MDT \tag{7}$$

Previous definitions consider revealed failures. When considering unrevealed failures (e.g. failures in safety equipment), the state of the equipment is tested with time intervals of T. As the failures can take place at any time during the test interval but will not be revealed until the test is carried out, the mean down time will be in the middle of the test interval. In these cases unavailability is:

$$Un = \lambda \frac{T}{2} \tag{8}$$

2.4 Key performance indicators

Maintenance performance, the achieved or expected result of actively using resources to retain an item in or restore it to a state where it can perform required functions, is measured using key performance indicators (KPIs). European standard EN 15341 (2007) provides a collection of KPIs and explains their use. Using right KPIs enables the organization to measure the state of operations, evaluate and compare performance, identify strengths and weaknesses, and control progression and changes over time. Measuring and analysing KPIs helps to set objectives, plan strategies and actions, and to share results to inform and motivate employees. They can be used as periodic budgeting and performance assessment tools or on a spot basis for auditing and benchmarking.

The standard divides KPIs into three categories: economical, technological and organizational. Additionally they are divided to three levels indicating the detail of information they produce. For example, level 1 economic indicators compare total maintenance costs to different factors, whereas level 3 indicators compare maintenance type specific costs to overall maintenance costs. Most indicators can be used at different organizational or process levels. When KPIs are used to examine some entity, be it a plant, process, sub process or individual equipment, it must be ensured that used factors refer to the same entity and to the same time frame.

All KPIs presented in the EN 15341 (2007) require source data from the examined plant, operation, process or equipment. For a maintenance service provider, many of the needed factors can be unavailable, for example production output during the examination period might be information that the customer does not want to disclose. However, the factors needed to calculate technical key indicators should have better availability. For example, previously introduced reliability metrics MTBF, MTTF and MTTR belong to these indicators.

2.5 Maintenance management

Maintenance management consists of all managerial tasks used to determine maintenance objectives, strategies and responsibilities, and their implementation by planning, controlling, improving and other such actions.

Maintenance objectives are targets that are assigned to maintenance activities. As stated before, basic objective of maintenance is to retain or restore an item to state where it can perform required functions. However, for practical reasons there usually are other objectives for maintenance activities as well. These can be based on factors such as available maintenance resources, production targets, and laws and regulations.

Maintenance strategies are methods that are used to achieve maintenance targets. In the simplest sense, this means choosing the most suitable maintenance type for the maintained item. In practise the maintained systems are so complex that a maintenance strategy must consist of decisions based on deep system analysis to be effective. Additionally, the strategy can include such decisions as outsourcing some activities and allocating resources according to criticality of different tasks.

Implementation of a maintenance strategy includes planning the tasks, resource use and the timetable, controlling the maintenance activities and preferably also improvement of said activities.

There are numerous different maintenance strategies that are applicable to process industry production plants. Simplest strategies are based on a plain corrective or preventive maintenance or on some combination of these. In plain corrective maintenance strategy, the items are maintained only when they fail. This strategy is very ineffective and can accumulate significant costs as production losses are high. Plants utilizing only corrective maintenance are extremely scarce. (Gulati, 2013)

Preventive maintenance aims to prevent failures by conducting periodic maintenance tasks to items. These tasks either increase the remaining item life time (e.g. lubrication) or reset it (e.g. changing a wear part). In a simple preventive maintenance strategy maintenance is planned according to instructions provided by the equipment supplier or just plain guessing. More sophisticated ways to plan maintenance can include utilization of past experience obtained using the same or similar equipment and possible data obtained from maintenance operations. Preventive maintenance cannot completely remove the possibility of failures and therefore need for corrective maintenance actions will never be completely removed. (Gulati, 2013)

Need for higher efficiency, increase in system reliability and better cost efficiency have contributed in the formulation of more sophisticated maintenance strategies that incorporate the use of different system analysis tools and mixtures of different maintenance types based on such factors as item criticality. This development in maintenance management methods is illustrated in the Figure 2.

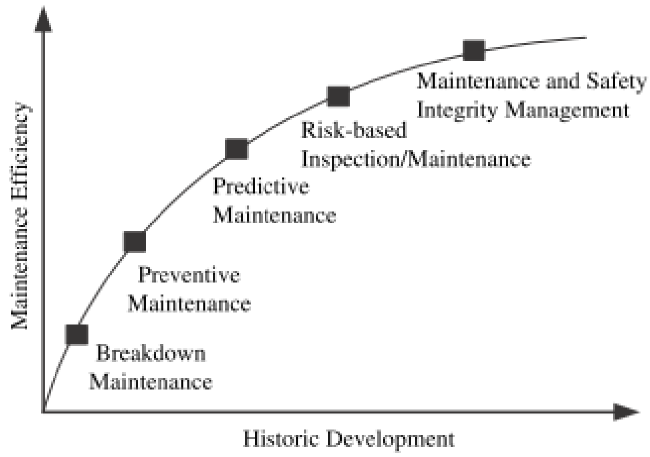


Figure 2: Maintenance models and their corresponding maintenance efficiency (Wang, Liu, Zhong, Yang, & Yuan, 2011)

One of the most used maintenance strategies; Reliability-centred Maintenance; is described in the following subchapter. It is used as an example as it was the go-to methodology for the maintenance planning of service product management of many technology areas at the subject company of this thesis.

2.6 Reliability Centred Maintenance

Reliability centred maintenance (RCM) is a maintenance management and planning methodology used to plan preventive maintenance programs. It approaches systems from functionality point-of-view and aims to increase functional reliability to the inherent level of the system, in other words to the level that the system can reach without the need to redesign. Additionally it addresses safety and economic aspects of the subject system.

RCM has its roots in the aircraft and aerospace industry. It is based on findings of a reliability survey conducted by U.S. Federal Aviation Authority in the beginning of the 1960s about factors affecting reliability and efficacy of preventive maintenance. (Sherwin, 1999) RCM has gone through several modifications throughout the years, latest of them being the MSG-3 that is described in standard SFS-IEC 60300-3-11:2001 by the International Electrotechnical Commission. RCM is commonly used due to its straightforwardness and easy applicability. Its use does not require a need for understanding of complex mathematical models.

On the theoretical side, the basic idea behind RCM methodology is that by examining the subject system through functions it is required to perform, a comprehensive maintenance plan can be produced with lower effort than by analysing the failure behaviour of all system components. (SFS-IEC 60300-3-11, 2001)

RCM is widely used on production plants within different industries, including minerals processing and metals manufacturing plants. Due to its easy applicability, it is also the go-to method for maintenance recommendation development on several service product management teams at the subject company.

The development of a preventive maintenance plan using RCM is a two-step process. First, the functionally significant items (FSIs) are identified. In the subject system FSIs are such items, whose failure can affect safety, be undetectable during operation, have significant operational impact or have a significant economic impact. On the second step, applicable preventive maintenance tasks are identified for the FSIs. This is done using a decision logic tree. Both steps have several tasks. (SFS-IEC 60300-3-11, 2001)

Identification of FSIs begins with collection of system information. Collected materials should include all available information on the requirements for equipment and associated systems, design and maintenance documentation and performance feedback including maintenance and failure data. (SFS-IEC 60300-3-11, 2001)

Next, a system analysis is performed. Systems are identified by partitioning analysed equipment into systems, groups of components that provide well identified functions and have unequivocal borders. If the identified systems are considered too complex, they can be further divided into subsystems that perform a function critical to parent system performance. Results of are recorded to a master system index. (SFS-IEC 60300-3-11, 2001)

The system functions are identified for systems and subsystems. Both main and auxiliary functions are determined using such tools as reliability block diagrams. The definition of functions should include actions and requirements the system or subsystem should accomplish. Functions are identified for all possible modes of operation, including safety, abnormal operation and emergency instructions. System functions can be identified using design specifications and descriptions, and operating procedures. Identified functions are collected into a list of system functions. (SFS-IEC 60300-3-11, 2001)

After the functions are listed, they are prioritized. Prioritization can be done using qualitative and/or quantitative methods. (SFS-IEC 60300-3-11, 2001)

Next, functional failure modes for the system functions are identified and classified. A functional failure is a component failure that causes the system to lose its ability to perform one or several of its required functions. Classification of these failures is made by determining their impacts on safety, availability and maintenance costs, and ranking the failures by their severity. This ranking is considered the most important part of the analysis as it affects the performance of the produced maintenance plan. Too conservative ranking leads to an excessive, costly maintenance plan and too incautious ranking results to excessive failures and decreased safety. (SFS-IEC 60300-3-11, 2001)

Using the list of systems and their functions, function priorities, function failures and failure ranking, the functionally significant items are identified. These items are exposed to further analysis to identify their function, functional failures, failure causes and failure effects. This task must be completed for each FSI before the preventive maintenance task selection can be started. Thorough FSI analysis makes it possible to identify critical FSIs; the ones with both high failure probability and significant functional effects or medium failure rate but high criticality. (SFS-IEC 60300-3-11, 2001)

FSI analysis can be done utilizing such tools as FMEA or FMECA. These tools are described in greater detail in Chapter 5.2. However, it must be noted that FMEA and FMECA used in RCM system analysis concentrates on functional aspects of the systems, whereas the traditional FMEA and FMECA consider all failure modes of the equipment. (SFS-IEC 60300-3-11, 2001)

When the FSI analysis is fully completed, the RCM moves to its second step, maintenance task selection. This step is largely based on use of a YES/NO-logic tree. First level of the tree divides the functional failures into categories based to their effects and the second one provides a suitable maintenance task to counter the failure. IEC 603000-3-11 offers a sophisticated decision logic tree for the task selection, but also simpler versions are available. (Rausand, 1998)

The available maintenance tasks are: lubrication or servicing; operational, visual or automated check; inspection, functional check or condition monitoring; restoration; discard; redesign and no task. Each task has selection criteria on application and on safety effectiveness, operational effectiveness and direct cost effectiveness. (SFS-IEC 60300-3-11, 2001)

After suitable maintenance tasks are selected, their frequencies or intervals are defined. When possible, interval selection should be based on past use experience, be it on prior experience on similar equipment that proves the applicability and effectiveness of the task, test data provided by the manufacturer or reliability data on predictions. If these information sources are not available, the interval is determined using expert opinion. (SFS-IEC 60300-3-11, 2001)

In practice maintenance tasks are grouped in maintenance packages that include several maintenance tasks carried out simultaneously or in a certain sequence. This is typically the case in metallurgical process plants where production is continuous or a combination of continuous and batch processes, and therefore preventive maintenance is usually carried out during maintenance shutdowns. In these cases, maintenance packages must be treated as single entities and intervals are selected for the whole package. (Rausand, 1998)

Item replacements should be timed so that items having failures with effects on safety are changed with intervals that minimize the probability of failure. For items that affect only the system availability, the interval is determined comparing maintenance costs and costs of production losses. There are mathematical models that can be used for maintenance interval optimization, but they require extensive reliability data to be applicable. (Rausand, 1998)

Documentation on the task selection should include estimations in safety aspects and cost estimations related to carrying out each task. (SFS-IEC 60300-3-11, 2001)

Maintenance task interval selection concludes the RCM maintenance plan development. Its result is the initial maintenance plan that can be deployed to the field. During the use of this plan, data is collected on detected failures and carried out maintenance. This data can and should be used to revise the maintenance plan with regular intervals. (SFS-IEC 60300-3-11, 2001)

Basic RCM analysis does not take into account the uncertainty induced by the inaccurate or unavailable reliability data and other uncertainties in initial analysis. This can be a serious problem if no reliability data or past experience on the subject equipment is available. Selvik and Aven (2011) present an updated extension to RCM called reliability and risk centred maintenance (RRCM), which adds an easily adaptable way to include uncertainty analysis in PM task selection and PM interval definition activities.

The assumption that concentration on equipment functions can produce adequate analysis on system reliability is facilitated by interpretation of the bathtub curve, a generalization of component failure behaviour. There is considered to be six basic failure behaviour models. The failure behaviour of any component can be modelled using one of these models. The bath tub curve tries to answer the problem of modelling a system with multiple components with different behaviours. (Gulati, 2013)

On the bathtub curve two areas of increased failure rate can be observed, one at the beginning of the lifetime and another at the end of life time. At the beginning of the lifetime, the failure rate is higher because of infant failures due to faulty parts and low quality fitting. Failure rate decreases as the components with infant failures are located and replaced. In the middle of the life time failure rate stabilizes to a lower level as only random failures occur. At the end of the lifetime wear out failures become dominant and the failure rate increases. The bathtub curve is illustrated in Figure 3. (Gulati, 2013)

In RCM the failure behaviour of all systems is estimated to be following the bathtub curve. This is used to reason that excess maintenance should be avoided, not only because it increased maintenance and spare part costs but also, because it exposes the system to decreased reliability due to infant failures present after the maintenance.

Serwin (1999 & 2000) has raised arguments against the fundamentals of RCM. He resists the use of bathtub curve and raises doubts on the prioritization of data collection during the use of the produced maintenance plan.

When analysing FSI failure behaviour and setting task intervals, analysts can easily use the bathtub curve as the basis of decision making if they do not have adequate reliability data at hand. However, this is a questionable practice as the bathtub curve is in essence an equipment level approximation of failure behaviour. (Sherwin, 1999) It is true, that some components do express similar failure behaviour, but it is estimated that they present fewer than 5 % of all used components. (Gulati, 2013) Additionally, the RCM methodology does not consider the fact that used maintenance plan affects the bathtub curve of the equipment. Therefore using the curve to set said maintenance plan is problematic. (Sherwin, 1999)

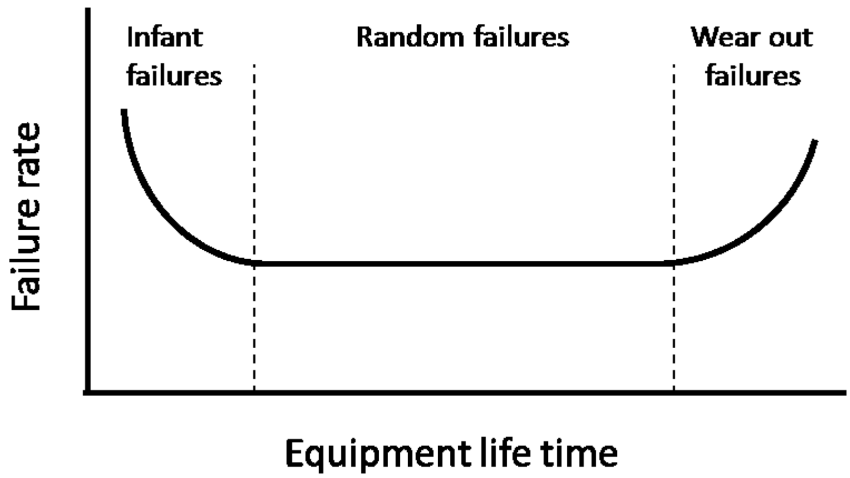


Figure 3. Failure rate bathtub curve

Additionally Sherwin (2000) thinks the RCM methodology is erroneous in the assumption that the most effective way to reduce infant failures is to avoid regular overhauls and replacement of parts as poor parts and bad fittings increase the probability of infant failures. This might have been an acceptable approach on the 1960s and RCM has kept hold of this reasoning to this day. However, it is argued that today the probability of infant failures can be more effectively decreased by spare part quality control and offering adequate training for the maintenance personnel. (Sherwin, 2000)

When discussing the data collection during the execution of RCM maintenance plan, Sherwin (1999) notes that RCM easily steers the data collection efforts to concentrate only in recording data about the FSIs. Recording reliability data on non-FSIs is as important as on FSIs, as maintenance carried out to non-FSI items contributes to the total life cycle cost of the equipment. Even if single maintenance actions on non-FSI items might seem cheap, they can cause large cumulative costs whose source can be hard to pin-point and that can be hard to correct if adequate data is not collected. Additionally, serious accidents are usually consequences of several smaller failures taking place simultaneously be change. This contributes to the importance of recording data on failures that were not classified as functionally significant during initial RCM. (Sherwin, 2000)

Previous description of RCM is used as an example of importance of reliability data and its collection. Other maintenance planning methods are just as dependent on adequate use experience data as RCM. Due to the large install base of different products of the subject company, there is strong believe in the company, that collecting user experience data from the installed base can provide a substantial amount of reliability data and offer a great opportunity to improve the quality of produced maintenance services.

Next chapter describes data collection from the view point of installed base information.

3 Installed Base Information

This chapter introduces the concept of installed base information and describes its value to an OEM-service provider.

3.1 Motivation for installed base data collection

When discussing industrial services, OEM companies have several advantages as service providers compared with traditional service companies. They can have lower customer acquisition costs, lower knowledge acquisition costs and lower capital requirements. (Oliva & Kallenberg, 2003)

However, transferring towards service business also brings new challenges, one of which is demand management. (Auramo & Ala-Risku, 2005) Demand management is the practice of coordinating and controlling demand sources to assure efficient service production and timely delivery (Chase, Jacobs, & Aquilano, 2004). Auramo and Ala-Risku (2005) have identified management of installed base information as an important tool in demand management for manufacturing companies transferring towards being or already acting as service providers.

One main aspects of successfully offering industrial services is to understand customer needs. (Auramo & Ala-Risku, 2005) In the case of this thesis, the problem is mostly approached from the view-point of maintenance services. IBI can be used to improve service operations, utilized in equipment reliability analysis to support both product development and maintenance service product management and to support marketing by providing input data for life-cycle cost analysis and references for a proof of concept.

An installed base is defined in the Cambridge Business English dictionary (2011) as the amount of equipment units delivered to and being in use by the customer. Typically, this definition is further developed as a set of equipment in use, where each equipment individual is handled as an individual item (Longman, 2007). This enables the development of term installed base information (IBI); an ensemble of data on equipment individuals, such as their location, owner, application area and service actions delivered to them. (Ala-Risku, 2009)

Maintaining installed base information helps the service provider to stay informed on the current condition of equipment in the install base and thereafter able to satisfy customer's expectations on equipment performance. The condition information can include past services delivered to the equipment and estimation for scheduled and sudden service needs. (Auramo and Ala-Risku, 2005)

Collected information can also be used to analyse the performance and failure behaviour of a product or item group. Several sources note (Gruhn & Cheddie, 2006) (Ala-Risku, 2009) (Auramo & Ala-Risku, 2005) that this information can be very valuable for product development functions of the OEM company. Using actual field-based performance data (e.g. failure rate) in product design or the redesign phase can induce notable savings compared with design iteration after the manufacturing of a new product has started.

Concentrating on maintenance services, different reliability and availability analysis tools constitute an important way of assess and improve the service. All these tools rely heavily on the availability of adequate reliability and maintenance data from actual, functional equipment under operational use. This data acts also as a basis for all the typical key performance indicators used to validate service performance. (Wang, Liu, Zhong, Yang, & Yuan, 2011)

3.2 Data to be collected

Ala-Risku (2009) studies installed base information utilization in four manufacturing companies that have been transforming their operations towards providing services. He identified three major categories of useful information to be collected from the installed base:

- Item data, information related to products of interest (Installed or serviced by the company)
- Event data, information related to the service actions of the company

- Location data, information related to the customer site or process phase that is the target of product deliveries and service operations.

Ala-Risku (2009) points out that there are differences on how companies on different fields are organizing information in these classes. Component providers typically consider the information of items as attributes of locations whereas for equipment provider locations are equipment attributes.

On the other hand ISO Standard 14224 recommends the following structure:

- Equipment unit data
    - Classification data, e.g. industry, plant, location, system;
    - Equipment attributes, e.g. manufacturer's data, design characteristics;
    - Operation data, e.g. operating mode, operating power, environment.
- Failure data
    - Identification data, e.g. failure record number and related equipment that has failed;
    - Failure data for characterizing a failure, e.g. failure date, items failed failure impact, failure mode, failure cause, failure detection method.
- Maintenance data
    - Identification data, e.g. Maintenance record number, related failure and/or equipment record;
    - Parameters characterizing a maintenance action, e.g. date of maintenance, maintenance category, maintenance activity, impact of maintenance, items maintained;

- Used maintenance resources, including man-hours per discipline and total, and utility equipment/resources applied;
- Maintenance time including active maintenance time and caused total downtime.

Compared with Ala-Risku's (2009) model, the standard clearly has location data as equipment attribute and has divided event data into failure data and maintenance data. One reason for the difference might be the different approach on the storage database. ISO 14224 recommends an approach where the data is stored in a single database, whereas Ala-Risku's (2009) opinion is that different types of data can be storage in individual databases.

This thesis concentrates in enhancing value production in service deliveries through improving the capability to analyse and utilize cumulated service experience.

4 Method overview

This chapter gives an overview of the proposed installed base information (IBI) collection and analysis process.

As the main purpose of the proposed IBI collection process is to support service delivery development and life cycle cost analysis, the focus was on maintenance service reporting. The main phases of the process are presented in the Figure 4.

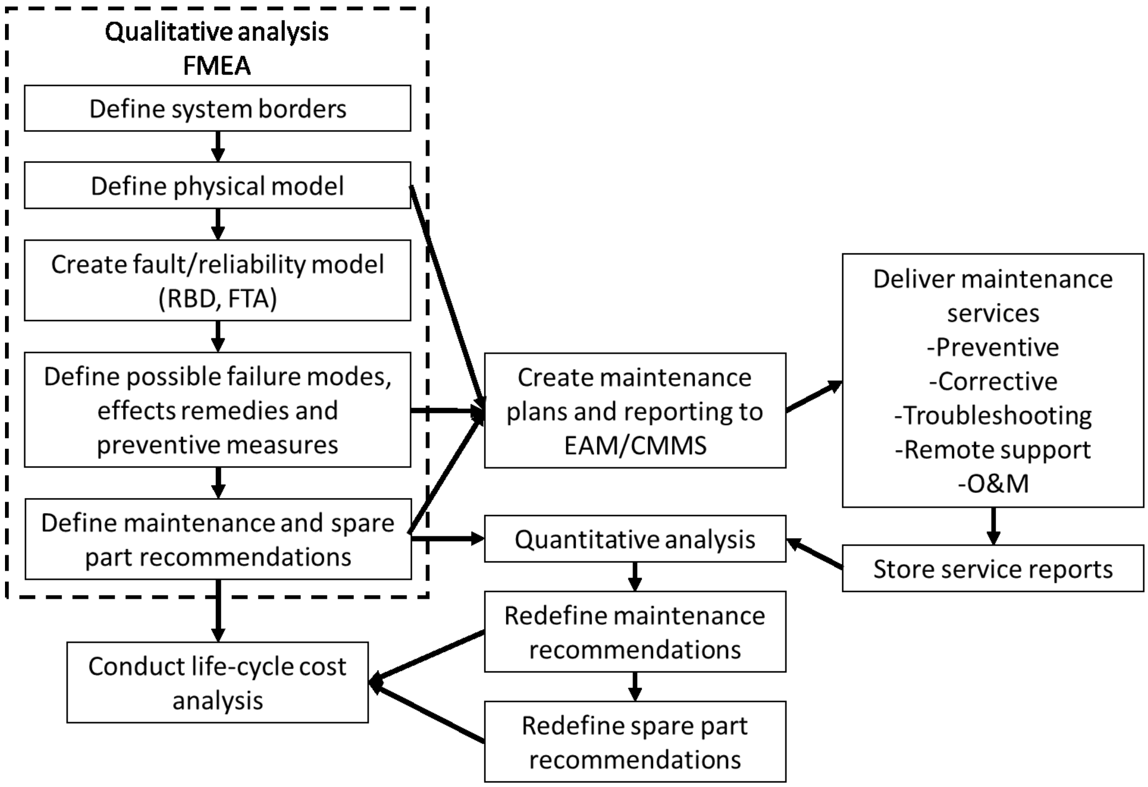


Figure 4: Product reliability analysis framework

The process begins with qualitative reliability analysis of the examined system. After the qualitative analysis is ready, the produced model and historical data is used to quantify the frequency of different failures. (SFS-5438, 1988) It is recommended that the qualitative system analysis is conducted during design and development of a new product, but can also be conducted to a product that is already in use.

The depth of the analysis should be proportionate to the intrinsic hazards. Both the magnitude of the hazards and complexity of the system define the needed degree of robustness and level of detail of analysis that is needed to reduce the risks to a reasonable level. In this context the term ALARP, “as low as reasonably practicable,” is typically used (Roberge, 2007).

Qualitative analysis begins with defining the system boundaries. In the product-service provider context, the system is typically the OEM product, but can be expanded to include auxiliary devices or even entire process lines. In the latter case, the analysed line consists typically of several units of similar machines and their auxiliary equipment. (SFS-5438, 1988)

Boundary definition should include: general description of the system, system interfaces and their physical and functional connection to other systems, definition of the operational environment, definition of energy, material and information crossing the interfaces, and definition of operational and other restrictions that are in effect on the analysis to be valid. (SFS-IEC 60300-3-9, 2000)

After the system borders are defined, a structural model of the product is constructed. This model describes the physical resources that constitute the system and connections of these resources.

Based on the structural model and available experience on the analysed system, a reliability block diagram is constructed. It helps the analysts to understand the relations between the components and how a failing part in the system can affect the operation of others. (SFS-5438, 1988)

As the structure is analysed and components are identified, the failure mode and effect identification can be started. Use of time and resources should be prioritized to the failure mode identification, because following steps of the overall process are heavily dependent on the coverage of identified failure modes. Additionally, the quality of the analysis decreases dramatically if some frequent failure modes are left unidentified. (Gruhn & Cheddie, 2006)

A failure cause, effect and relative importance are defined for each failure. These are used to define possible failure indication methods and isolation methods. Produced qualitative data can then be used to create preliminary recommendations for maintenance and spare part usage. It must be noted that as these recommendations are based on qualitative analysis only, they are not the best possible equipment reliability-wise. Therefore they have to be revised after a quantitative reliability analysis. Additionally, the product-service provider has to make a decision on how comprehensive maintenance and spare part recommendations it wants to provide to customers who are maintaining their equipment by themselves.

Preliminary maintenance and spare part analysis can additionally be used to estimate the costs of the operational phase of the product when conducting life cycle cost analysis. (Woodward, 1997)

When previous phases have been completed, the information can be used to set up a reporting structure in an enterprise asset management system (EAM) or a computerized maintenance management system (CMMS). This aspect of utilizing results from qualitative FMEA or FMECA was brought up on several of the interviews conducted for this thesis. These both ease the implementation of new products to EAM/CMMS and later the utilization of information collected from the EAM/CMMS.

After the recommendations and reporting infrastructure is in place, delivered services are reported using EAM/CMMS. The system stores reports and they can be summarized and exported from the system when adequate amount of data is collected.

Exported data on delivered service events is used in quantitative reliability analysis. The previously started FMEA analysis is developed into FMECA by defining criticality of the failure events and their frequency under the current maintenance plan. If new failure types are identified from the collected data, these should be qualitatively analysed and later quantified with original failures.

After the quantification is completed and critical parts and failure modes are identified, maintenance and spare part recommendations can be adjusted to better counter the failures with largest effect on reliability.

After the recommendations are updated, a new life cycle costing analysis can be conducted with revised maintenance needs and additionally with information on realized maintenance costs gained from the service event history.

The following chapters dive deeper in the different stages of the described process.

5 Analysis tools

This chapter describes the different tools and applications that utilize reliability and availability data. These tools are used to analyse different aspects of equipment and process reliability, availability and life-time costs in the proposed IBI collection and analysis method.

5.1 Reliability methodologies

Different methodologies used in reliability work can be roughly classified to four groups. On the most general level are the guidelines that describe the process, general steps, reporting and actions included in reliability analysis. The processes covered in the guidelines use System-level models that describe reliability aspects of a single product. These models utilize the next two classes, Component-level metrics and Mathematical models. The metrics define the reliability characteristic of a single component and models are used for numerical reliability analysis. The classification is illustrated in Figure 5.

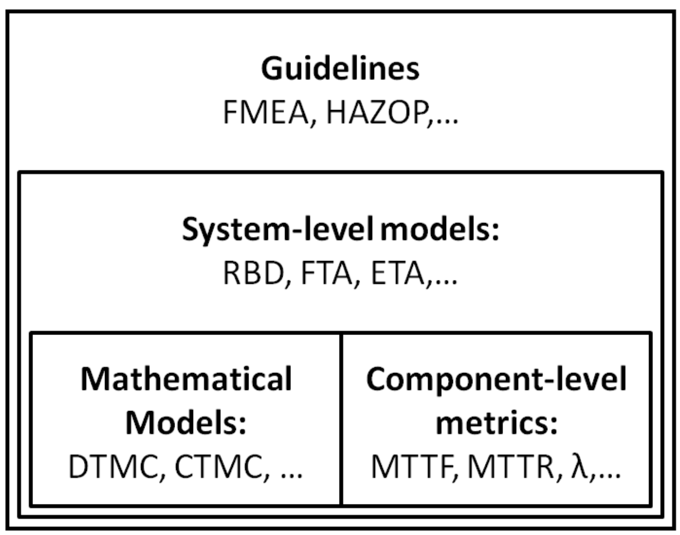


Figure 5: Rough classification of reliability methodologies

5.2 Failure Mode and Effect Analysis and Failure Mode, Effect and Criticality Analyses

Failure Mode and Effect Analysis (FMEA) is a traditionally used and well standardized qualitative reliability analysis methodology. It is an inductive method that can be used to perform a bottom-up system reliability or safety analysis. FMEA is based on component or subsystem level to which primary failure modes can be defined. The analysis defines the relations between component failures, system failures, operational malfunctions and decrease in performance. (SFS-5438, 1988) However, specifying the mechanisms or events leading to a failure are not in the main focus of the analysis (Roberge, 2007). FMEA can be expanded to include human errors and software errors in equipment with automation, but these are not part of the qualitative analyses.

FMEA can further be developed into Failure Mode, Effect and Criticality Analysis (FMECA). Effects of failures are described with criticality, which is presented with classes or levels. These describe the damages and hazards that can result from the decrease of system performance. In this sense, FMECA is used to quantify the results of FMEA. (SFS-5438, 1988)

FMEA has several applications, which include production of a logical system model used to estimate failure probabilities, helping to define information recording needs during the operation period of the equipment and production of information for maintenance planning. (SFS-5438, 1988)

Effectiveness of both FMEA and FMECA is increased if it is used to analyse items that can cause the entire system to fail. However, there are several weaknesses in FMEA and FMECA. As the analysis requires a hierarchical system model, it can become very laborious to perform if the system consists of multiple functions and multiple functional items. High system complexity leads to large amount of information that must be processed. If preventive actions are taken to account, the work load increases even more. (SFS-5438, 1988)

Additionally, coping human errors or multiple simultaneous failures with FMEA or FMECA is difficult, which decreases their effectiveness. This is a notable disadvantage as most common cause failures are caused by a mixture of human error and environmental causes. (Roberge, 2007)

FMEA and FMECA are optimized for mechanical and electrical equipment. This can cause difficulties when applying them to process equipment or full processes. (Roberge, 2007)

Qualitative FMEA requires following source information: a list of parts composing the system, their characteristics, performance, tasks and functions, relations between parts, redundancy rate and structure of redundant parts, and if possible the location of the analysed system in larger operational context. Information about functions, characteristics and performance must be available from all examination levels. (SFS-5438, 1988)

Applying FMEA begins by defining system performance boundaries with both nominal and minimal operation requirements. Next, operation and reliability block diagrams are constructed. They can be supplemented with additional models, such as failure tree models, if applicable. After the models are ready, a suitable documentation template can be created for results of the analysis. (SFS-5438, 1988)

The analysis phase starts by defining failure modes, causes and effects, and their relative importance and order. Then, detection methods, isolation possibilities and isolation methods are developed for the found failure modes. After these steps, it is possible to define design and operational safety precautions to counter extreme events. If conducting FMECA, analysis can be taken further to define the criticality and probabilities of different events. (SFS-5438, 1988) Detailed list of defined item characteristics is presented in Table 1 (Roberge, 2007)

There are several possible ways for failure mode identification. If analysing new components, it is possible to use historical information of old components, which have similar operation and structure. When observing a commonly used component, previous use experiences in other applications can be used. These can be documented in operational records, failure reports or a record of laboratory tests. If the component is complex, it can be divided into smaller entities that are analysed qualitatively. Lastly, the failure modes can be derived from the typical operation and physical parameters of the component. (SFS-5438, 1988)

Table 1: Component failure characteristics defined in FMEA and FMECA

FMEA:
Component name
Function of component
Possible failure modes
Causes of failure
How failures are detected
Effects of failure on primary system function
Effects of failure on other components
Necessary preventive/repair action
FMECA:
Rating of failure frequency
Rating of severity of failure (i.e. consequence)

For each identified failure mode, causes and effects are identified and described. A single failure mode can have several causes and each of them should be specified. This has to be done for estimation of probabilities and ramifications, and selection of effective corrective actions to be possible. Effects of a failure to the function or state of the analysed system are identified and listed. Effects should be analysed on all levels of the system, starting from failed item and ending with effects on the whole system. Estimated failure detection methods are also listed. (SFS-5438, 1988)

Failure criticality is estimated by quantifying failure probability and failure effect. In this context, effects are extended to include personnel, environment, external equipment and production efficiency. As these variables are otherwise hard to quantify, they are typically assigned a monetary cost. Final criticality values are gained by calculating expectation values of costs for every failure using its probability and estimated cost. (SFS-5438, 1988)

Results of the FMEA or FMECA are reported with description of the analysis method, used level of analysis, and list of used assumptions and premises of the study. Additionally, the following topics can be discussed: recommendations to product designers, maintenance personnel and system users, failures that can individually cause serious harm, and design alterations that have already been performed due to the analysis. (SFS-5438, 1988)

Other analysis tools, such as reliability block diagrams or failure and event trees can be used when carrying out the functional modelling of the system. These tools are also valuable in quantifying the criticality of failures.

5.3 Reliability Block Diagram

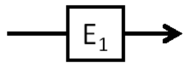
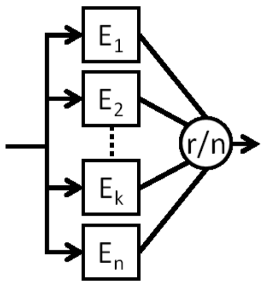
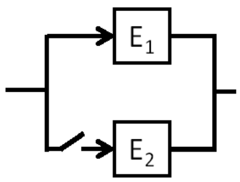
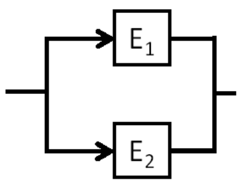
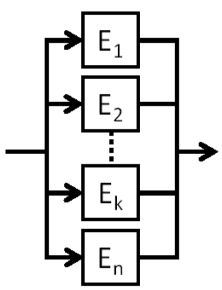
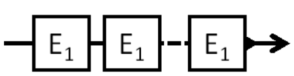
The reliability block diagram is a simple way to model the configuration and operation of either larger systems with several equipment units or single devices with moderate or high complexity. In the diagram each sub-unit is illustrated as a single block. These blocks can be situated either in series or in parallel. Blocks representing items that can individually bring the whole system down when they fail are drawn in series. If there are two or more items, all of which are needed to fail for the system to fail, they are drawn parallel. (Gruhn & Cheddie, 2006)

Several rules should be kept in mind when setting the block definitions. To simplify the diagram, the number of components represented by one block should be as large as possible. At the same time, the function of a single block should be easily identified. There should be no dependency between blocks, meaning that a failure in one block should not affect the probability of failure in another block. Redundancy inside blocks should be avoided because it renders definition of failure rates within blocks invalid. Any replaceable units should form individual blocks. The environment should not change within one block. (Smith, 2011)

The failure rate for each block is determined separately. This can be done using equipment history information or expert estimations. (Smith, 2011)

Basic mathematical operations in RBD analysis are fairly simple. Probabilities or failure rates of blocks in series are added and blocks in parallel are multiplied (Gruhn & Cheddie, 2006). In addition several more complex models have also been developed (Borouni, 2013). These are visualized in Table 2.

Table 2: Alternative mathematical models for Reliability Block Diagram

	Simple element	$A = \frac{\mu}{\lambda + \mu}$
	Redundancy r/n	$A = \sum_{k=r}^{n} \frac{c_n^k \mu^k \lambda^{n-k}}{(\lambda + \mu)^n}$
	Standby	$A = \frac{\mu^2 + 2 \cdot \mu\lambda}{\mu^2 + 2 \cdot \mu\lambda + \lambda^2}$
	Active Redundancy (Parallel)	$A = \frac{2 \cdot \mu^2 + 2 \cdot \mu\lambda}{2 \cdot \mu^2 + 2 \cdot \mu\lambda + \lambda^2}$
	Active Redundancy with n elements	$A = 1 - \prod_{i=1}^{n} \left(\frac{\lambda_i}{\lambda_i + \mu_i} \right)$
	In series with n elements	$A = \prod_{i=1}^{n} \left(\frac{\mu_i}{\lambda_i + \mu_i} \right)$

Kim (2011) has developed an improved version of reliability block diagram with general gates (RBDGG). The method adds AND-, OR- and k-out-of-n-gates to traditional RDB. This makes the method more versatile and Kim argues that it is more intuitive and easier to use than other reliability analysis methods such as fault tree analysis.

Lisnianski (2007) has refined a reliability block diagram method to be applicable to multi-state reparable systems. In this method, the items (blocks) have changes in their stages modelled as Markov nets. This method is argued to be able to model complex multi-state systems with n simple models of system elements instead of building single complex model of the whole system.

5.4 Failure Tree Analysis

Fault trees are logical structures where the top event is connected with sub events through logic gates. Whereas reliability block diagrams are used to analyse the reliability of larger complexes, fault tree analysis is applied to analyse cause relations and predicting probabilities behind specific system failures. These failure modes are called top events. (Smith, 2011)

Fault tree analysis can be used for both qualitative and quantitative analysis. In qualitative analysis different cause relationships leading to the top event can be determined. In quantitative analysis, the probabilities of different event chains can be developed (Mannan, 2012a)

Fault trees consist of the following elements: the top event, primary events, intermediate events and logic gates. The top event is the undesired event whose development mechanism and probability are being analysed. Primary events are the events that are not developed any further. This means that they are either basic events that are not meaningful to develop further or events that take place outside of the predetermined system boundary. Intermediate events are located between the top and primary events and are used to describe the logic gate outputs. (Mannan, 2012a)

Logic gates are used to define the logic relating inputs to the outputs. Most typically used gates are the AND gate and OR gate. In addition there are EXCLUSIVE OR gates, PRIORITY AND gates and INHIBIT Gates. Properties of AND gate and OR are described in Figure 6 (Mannan, 2012a) and Table 3 (Borouni, 2013)

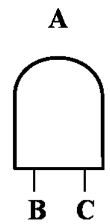
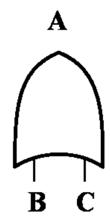
Gate	Logic Symbol	Boolean Algebra Relation	Probability Relations
AND		A = BC	P(A) = P(B)P(C)
OR		A = B + C	P(A) = P(B) + P(C) – P(B)P(C)

Figure 6: Failure tree logic gates, basic relations

Table 3: Possible inputs and outputs of AND and OR gates

Gate	Inputs	Outputs
OR	P_B OR P_C	$P_A = P_B + P_C - P_B P_C \approx P_B + P_C$
	F_B OR F_C	$F_A = F_B + F_C$
	F_B OR P_C	Not permitted
AND	P_B AND P_C	$P_A = p_B p_C$
	F_B AND F_C	Not permitted; reformulate
	F_B AND P_C	$F_A = F_B P_C$

Methodologically failure tree analysis is reversed in comparison to other analysis methods. Analysis is started with an unwanted top event and the tree is developed downward to define the underlying basic events. During the process possible failure mechanisms responsible for top event development are defined. (Roberge, 2007)

Qualitative failure tree analysis is used to identify combinations of basic events that are sufficient, when realized, to cause the top event. These combinations are called “cut sets.” (Roberge, 2007)

Failure tree analysis is an effective tool for studying failure development routes, especially when identifying secondary and tertiary causes. However, it requires experience from the analyst and due to the tree structure it is effective only on defining causes for single events. Therefore its use is reasonable in cases where the top event has severe consequences. Additionally, the amount of detailed data from basic event occurrence frequencies is needed, which further restricts its use. (Roberge, 2007)

5.5 Event Tree Analysis

Event trees or Cause Consequence Diagrams (CCDs) are tree structures that show the likely chain of events and can have multiple outcomes. Building blocks of the tree are decision boxes that include an event and a YES/NO outcome. Both outcomes are linked to new decision boxes or final outcomes with path lines. These kind of simple CCDs are easy to construct and to quantify. Quantification is done simply by multiplying the probabilities through each possible path. A simple example of an event tree is illustrated in Figure 7. (Smith, 2011)

When modelling continuous processes there can be situations where paths from decision boxes revisit earlier boxes. These so called feedback loops occur in situations where an outcome is reached only if certain circumstances apply. In these cases simple multiplication of probabilities does not give us the probability for the outcome. An example of a feedback loop is illustrated in Figure 8. (Smith, 2011)

In comparison to fault trees, event trees model the order in which the element fails. They allow easier modelling and are easier to follow for non-specialist personnel. Additionally they allow several outcomes and sequential events, permit intuitive exploration of outcomes, and permit feedback loops. (Smith, 2011)

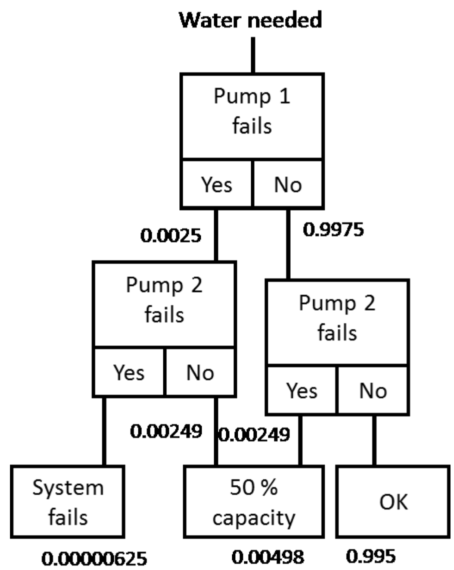


Figure 7: Simple Cause Consequence Diagram

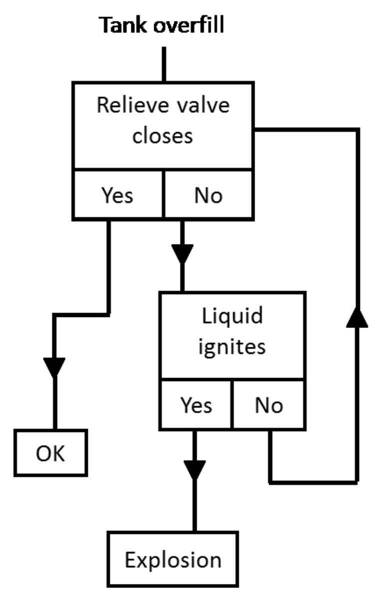


Figure 8: Example of CCD with a feedback loop

5.6 Life-cycle cost analysis

White and Ostwald (1976) define life cycle costs (LCC) of an item as “the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life." The term was first introduced in 1965 in a report by Logistics Management Institute (Dhillon, 2010).

LLC analysis can be conducted either as a predictive analysis or as a follow-up to past acquisition decisions. Predictive analysis tries to estimate LLC for a future investment whereas follow-up LCC is used to calculate realized LCC for equipment. The analysis counts total costs of the investment beginning from the purchasing of the asset to the end of its use using present value technique. (Woodward, 1997)

Life cycle cost analysis in different fields and industries has indicated that ownership costs of engineering systems can vary 10 – 100 times the initial acquisition cost. Up to 70 % of these costs can come from maintenance and maintainability costs. For these reasons life cycle cost analysis has become an important tool in acquisition management. Trends such as increasing global competition, increasing operation and maintenance costs, budget limitations, increasing technical sophistication leading to more expensive products and systems, rising inflation and increasing awareness of cost effectiveness among users have further increased the use of LCC analysis. (Dhillon, 2010)

Above listed reasons also give OEM and service providers' incentive to employ LCC analysis to produce data that can support sales and development of their products. This notion is supported by the notion that 70 – 85 % of the total life cycle cost of a product is committed during design of the product (Asiedu & Gu, 2008).

The objectives of life-cycle cost analysis are to enable investment options to be effectively evaluated, to consider the impact of all costs rather than only initial capital costs, to assist in effective management of completed projects and to facilitate a choice between competing alternatives. (Woodward, 1997)

Two terms are often mentioned when discussing the objectives of LCC analysis: cost drivers and trade-offs. Cost drivers are major cost elements that have significant impact on the life cycle cost of an investment option under observation (SFS-EN ISO 15663-1, 2000). Trade-off is a term used to describe a situation, where a choice must be made between two properties of an option (Woodward, 1997). A simplified example of a trade-off is for example a choice between an asset with high capital expenses and low operational expenses or asset with low capital expenses and high operational expenses.

Standard ISO 15663-1 (2000) describes a general procedure for conducting LCC analysis. The standard discusses LCC analysis from the view point of asset acquisition or design project. The procedure is divided in to four steps, that each includes several tasks. The steps are: diagnosing and scoping; data collection and structured breakdown of costs; analysis and modelling; reporting and decision making. The process is presented in Figure 9.

The process is iterative, which may cause such complications as a need to assess other technical options, challenge initial assumptions of the project, or respond to challenges outside of the borders of the analysis. Iteration is carried out so that after the first iteration is used to identify cost drivers and trade-offs, second iteration targets primary cost drivers to develop and assess alternatives options and third iteration does the same to secondary cost drivers. Iteration should be carried out to all cost drivers that are identified to have potential of creating value. However, all iterations do not have to include all tasks included in the overall process. (SFS-EN ISO 15663-1, 2000)

The first step, diagnosis and scoping, aims at development of fundamental understanding about the issues, relationships, assumptions and requirements of the analysis. During this step objects and constraints of the process are identified, decision criteria are established, potential options are identified and established and finally costs that are to be included in the analysis are defined. This step is the entry point of the process and is essential for the success of the overall process. (SFS-EN ISO 15663-1, 2000)

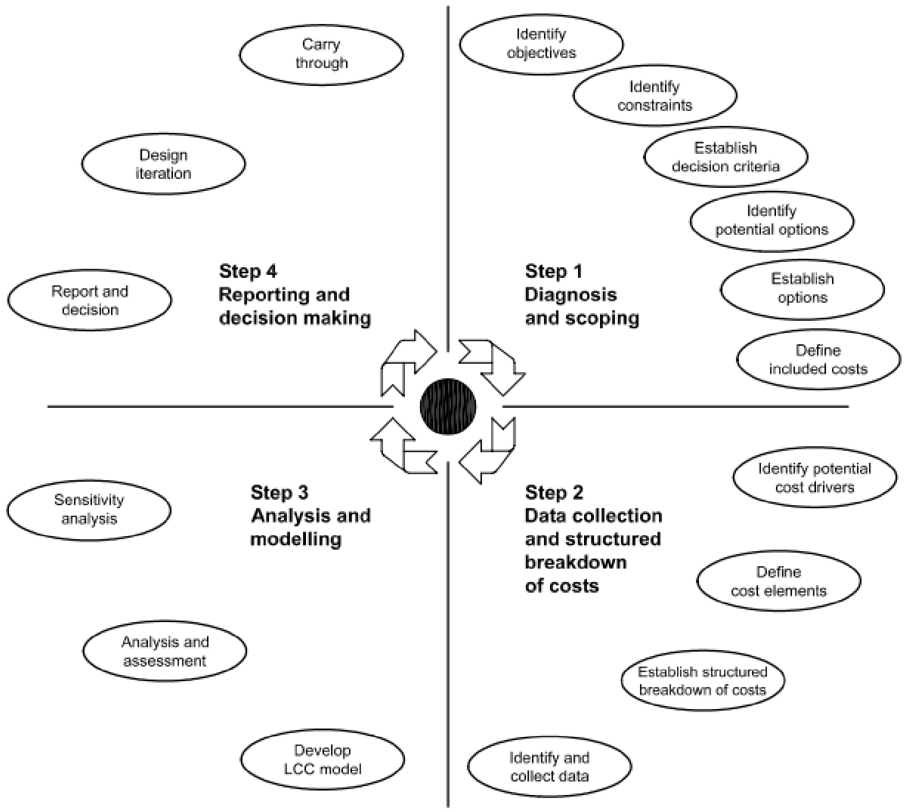


Figure 9: The life-cycle costing process (ISO 15663-1, 2000)

In the second step, data collection and structured breakdown of costs, objective is to define needed data by constructing a structured breakdown of costs and then to collect that data. The step begins with identifying potential cost drivers for each option under examination to help identify where the attention of the overall analysis should be concentrated. Then, the cost elements identified in the first step of the process are addressed and estimated to define the minimum level of detail that is needed to discriminate between options. After the cost elements are defined, they are organised to establish the structured breakdown of costs. Cost structure should take into account how the costs are acquired and recorded. As final tasks of the second step, the needed data is identified and collected. Data collection is essential for the success for life time costing as used data collection practice influences the way data is analysed and data quality affects the quality of the analysis. (SFS-EN ISO 15663-1, 2000)

The third step, Analysis and modelling, aims to predict the life-cycle costs for different options and to find differences between them. Through these differences, options are ranked. Additionally cost drivers are compared and analysed, sensitivity analysis is conducted to see which factors can change the ranking, and potential risks are identified. The step begins with developing the life-cycle cost model that fulfils the requirements set by the application and is simple enough for users to utilize, but simultaneously accurate enough so that it brings out the differences in options. The model is then used to analyse the data collected in the step two. (SFS-EN ISO 15663-1, 2000)

The initial results must be evaluated. The evaluation should cover the ranking of subject options in accordance with decision criteria, the life-cycle cost summaries of options and cost factors. Evaluation should answer such questions as: why some options are better than others, how the time at which the costs are realized differs between options and are individual cost totals in line with expectations. (SFS-EN ISO 15663-1, 2000)

After the initial results are found to be reasonable, sensitivity analysis can be conducted. This can begin with eliminating low ranking options by evaluating if there are such circumstances where they can reach the higher ranking options. To those options that can, the probability of corresponding situation change must be estimated. Options that do not possess the ability to rise in the ranking or are unlikely to do so can be eliminated from further analysis. For the remaining options, uncertainty of cost drivers and sensitivity to changing standard factors, such as oil price or exchange rates, are estimated. The shift needed to change the ranking between the options and its possibility should be assessed for these uncertainties and factor changes. (SFS-EN ISO 15663-1, 2000)

Final step of the process is reporting and decision making. The findings of the analysis are reported, the most economically viable solution for the subject asset is established and usage of this information on the decision making of next project phases. As new options might be found during the LCC analysis, this step also includes consideration in possible new iterations of the analysis. Possibility of subsequent work on the life-cycle costing in later project phases is also discussed. (SFS-EN ISO 15663-1, 2000)

The form of reporting has been established during step one. It must be noted that supporting arguments should be included in the report together with the results. This both establishes confidence in the results and eases the decision making for the next project phase. Recommendations may be in one or more of following three forms: presenting the preferred option, suggesting further iterations or proposal on future studies to be carried out during next project phases. As the recommendations for the next project phase are presented following matters should be considered: The ranking of options allows easier elimination of unsuitable options. Sensitivity analysis provides both arguments for recommended solution and identifies opportunities to improve it. Cost drives present the magnitude of the improvement through changes to existing options or definition of new options. (SFS-EN ISO 15663-1, 2000)

Iteration of the analysis might be needed to reduce uncertainty associated with existing options or to examine new options. Before iteration can be started, following questions should be answered: what further data is needed, what tasks are to be repeated, and is all work carried out earlier to be repeated with the same level of detail. (SFS-EN ISO 15663-1, 2000)

Lastly it must be noted that the final report on LCC analysis results should be included in the final project documentation. (SFS-EN ISO 15663-1, 2000) This helps the organization to keep track on the decisions and their arguments made during the project and offers a possibility to develop decision making practices during similar projects in the future.

Woodward (1997) notes, that one of the key cost factors of the asset life-cycle is maintenance costs during the operational phase of the asset life-cycle. Therefore the optimization of maintenance costs is essential to attain low operational costs. This requires a trade-off to be made between costs due to production losses during equipment downtime and costs produced by use of resources during maintenance operations.

In LCC analysis, the estimation of operational costs is based on predicted costs and actual experience on similar equipment. Therefore the collection of maintenance data from service events from different customer sites gives equipment and service provider unique opportunities to produce more accurate estimations on operation costs of provided equipment. Additionally, it opens a possibility to track service production costs against service selling prices. This information can be used to make strategic decisions on service product offering.

Data that should be collected from maintenance events are direct labour, spare and wear parts, materials, equipment, and external labour used to carry out the maintenance. (Woodward, 1997)

6 Data quality

In this chapter, challenges related to data quality are described.

In the reliability management there are two main reasons for collecting data: feedback resulting in modifications preventing further defects and acquisition of statistical reliability data. (Smith, 2011)

Any form of quantitative reliability or LCC analysis is strongly dependent on the quality of the data used as an input. (Center for Chemical Process Safety, 1998) Standard ISO 14224 (2006) gives the following requirements for data to be considered as high quality:

- Data should be complete in relation to specification;
- data should be in compliance with definitions of reliability parameters, data types and formats;
- accuracy of input, transfer, handling and storage of data should be on a high level, in both manual and electronic formats;
- data should have accurate population and an adequate surveillance period to give statistical confidence to the conducted analysis;
- data should be relevant to data user's needs.

However, every reliability data collection effort faces certain difficulties. Smith (2011) listed challenges that plant maintenance or quality management organizations can encounter:

- Inventories: Data can be divided between multiple sources and failure data can easily be separated from the inventory data. Even if the failure is described with precision, the information about corresponding item count and their running times at the moment of failure can be missing
- Motivation: Motivation of a field engineer to pay attention on reporting completed work affects greatly on the quality of acquired data. Motivation can be

severely decreased by things like unrealistic time standards, poor working conditions and inadequate instruction. Attention paid to reporting is usually the first thing getting neglected when a field engineer feels frustrated with his or hers work.

- Verification: Subsequent checking of reported data can be challenging once the report leaves the person filing it.

- Cost: Both compiling reports and interpreting them can consume hours of work. As this work can be transferred to costs, excessive, futile or poorly understandable reporting can cause high costs for data acquisition.

- Recording non-failures: This problem can arise in two ways. Firstly, there can be a culture of locating faults by replacing suspect components. Even if the replaced component is not the cause of the fault, it is not returned to the equipment but recorded as faulty. This inflates failure rates and depletes the spare part inventory. Secondly, there is a possibility of interpreting secondary failures as primary failures. This can happen when a failing component does not cause a system failure, but stresses another component, which in time fails causing the system to fail. When the system fault is diagnosed, both failures are found, but their occurrence sequence is not identified. This leads to both of them to be recorded as primary failures, which in turn inflates failure rates.

- The times to failure: For sufficient analysis of wear out and burn-in characteristics of different items, operation time at the time of failure is needed. This fact can be neglected in older plant records, as it requires each item to be individually identified.

From the view point of an external maintenance service provider, these challenges get even harder. During the conducted interviews, the following difficulties specific to service providers in the above described categories were identified:

- Inventory: Obtaining inventory and event data on new customer plants, especially on older equipment, is challenging. Running times and past maintenance activities are unknown and can be next to impossible to acquire, especially if the customer does not comply to turn over the data or does not have a proper data collection process in place.

- Motivation: Because of the role as a contractor, the field service engineer has reporting responsibility both to the customer and to his own organization. This causes additional work if the used reporting tools consist of filling paper reports on the field and transcribing the reports to an electronic reporting system at the home office. Time used for transcribing is lost from other tasks such as preparing for the next customer visit. When prioritizing work, the upcoming customer visits tend to win. Additionally, if the field service engineer thinks that the data he is reporting does not have any actual use, motivation to devote to reporting decreases even more.

- Verification: As individual field service engineers are the only knowledge holders about the sites they are responsible for, data verification can be difficult. This problem manifests itself in such situations where parties without day-to-day contact with the field service engineer access the data and when the original author of the reports is no longer part of the organization. Use of third party contractors to carry out tasks complicates data verification even more.

- Cost: Costs caused by extra work on data collection can increase significantly if the reporting system requires both paper and digital reporting. These costs must be covered with income from the customer and therefore they tend to drive the price of the service up.

- Recording non-failures: When providing corrective maintenance, the main priority of the service is to return the equipment to operational condition as fast as possible. This can cause maintenance activities to target items that have not failed and therefore skew the failure rates of items.

- The times to failure: In the case of preventive maintenance service, some or all failures may be left unrecorded if corrective maintenance is handled by customer organization. In the case of corrective maintenance inventory information on items maintained, such as running times, might be hard to come by and failure mode identification can be difficult.

Additionally recording item histories on spare part level can be impossible if maintenance responsibilities are divided between customer and service provider organizations. As standards of reliability data of different equipment are not consistent and there are numerous data systems used by different organizations, data exchange can be hard or even impossible (Wang, Liu, Zhong, Yang, & Yuan, 2011).

6.1 Data quality assurance

To counter difficulties described above, following requirements are suggested for information reporting system and used procedures:

Tools (e.g. paper report templates, reporting applications) should be as logical and easy to use as possible. This decreases the possibility of the report creator to make mistakes in reporting or to get frustrated and to neglect to report some of the desired information. In an ideal situation, reporting at the customer site should take advantage of mobile tools, such as tablet computers, that enable the field service engineer to digitally report activities without using paper forms. It must be noted that as customer sites can be located in remote areas and access to an internet connection might not be available, the electronic system must be operable in offline mode during the visit and able to update the reporting data to a centralized database when a connection is available.

To address both usability of the reporting system and information interpretation, many of the reported inputs should be predetermined. In the case of corrective maintenance, these include attributes such as the maintained item, failure mode and used corrective action. Correspondingly in preventive maintenance these include the maintained items and performed tasks.

As described in the Chapter 5.2, the operational structure together with possible failure modes, effects and remedies are defined using FMEA or FMECA. Produced functional and failure models should be used as a basis for constructing a taxonomic reporting structure. This structure is used in the application in the following way:

1. User chooses the device/machine entity worked on.
2. Reporting application offers a list that contains the components that constitute the machine. (If top level equipment structure is complex, there can be a mid-level before component level, e.g. functional unit, sub-assembly)
3. User chooses the component maintained
4. Application offers component-specific failure modes
5. User chooses the right failure mode
6. Application offers failure mode-specific effects
7. User chooses the detected effect
8. Application offers failure mode-specific remedies
9. User chooses the used remedy
10. Application enquires additional information (e.g. used time, resources, man-hours per discipline)

It must be noted that predetermination of failure characteristics is never fully conclusive and some failure modes, effects and possible remedies can go unnoticed during FMEA. Therefore it must be possible for the user to input attribute values in free text. This brings new challenges as the amount of predetermined attribute values must be adequate for effective reporting, but should not be so diverse, that finding right values becomes time-consuming and pushes the user to use the free text option.

When the mechanical structure of the equipment and the failure model of its components are integrated into the reporting system, both data input and interpretation of the data becomes easier and less time-consuming.

To counter the problem with decreasing motivation at the local service centres, it is recommended that they are involved in the RAM work involving their customers. To achieve this, reliability analysis tools and processes, such as the one described in this thesis, should be made easily available for the local service centres. This should also include training for the use of these tools.

Training of field service engineers should be used to increase reliability in failure mode identification. This should be supported by making results of FMEA and FMECA of different equipment types easily available to local service centres and their field service engineers.

7 Data sources

In this chapter, different available data sources are discussed. Chapter concentrates on data sources that were accessible or were becoming accessible by Outotec Service Organizations at the time this thesis was written. The company specific information was acquired from interviews (Interviewees A – G) conducted between November 2013 and February 2014.

7.1 Maintenance service customers

These customers are purchasing maintenance services including maintenance inspections, corrective maintenance and preventive maintenance. A combination of these service types is covered under Maintenance Service Agreement signed by the customer and Outotec. Each service product type is described in the following paragraphs.

Maintenance inspection is a service event, where an Outotec field service engineer conducts a thorough check up on the equipment. The inspection covers all aspects that are considered crucial to the operation of the equipment. After the inspection the condition of each component and the recommended maintenance actions are reported to the customer.

Corrective maintenance is focused in restoring equipment to a functional state after it has malfunctioned (SFS-EN 13306, 2010). The customer informs local Outotec Service Centre of the equipment malfunction and the Service Centre dispatches the needed resources to the customer site to carry out needed maintenance actions. After the task has been completed, the team reports the scope of carried out work to the customer and to the Service Centre.

In preventive maintenance, the goal is to increase equipment reliability through carrying out maintenance activities that decrease the probability of equipment malfunction. This is achieved with maintenance planning and complying with maintenance recommendations. Outotec offers both maintenance planning and actual preventive maintenance services to its customers. Maintenance planning can utilize information obtained from maintenance inspections.

At the time of the writing of this thesis, Outotec's maintenance service customer base was small. Additionally, the reporting practices of Service Centres delivering maintenance services to these customers varied greatly.

Possible data that can be extracted from field service visits are listed in Table 4.

Table 4. Information possible to acquire from maintenance customers

Maintenance inspections
• Equipment condition at the time of maintenance • Item runtime since previous maintenance • Failure behaviour since previous maintenance
Corrective Maintenance
• Failed item • Failure mode • Failure effect • Estimation of the failure cause • Used remedy • Used maintenance time • Needed resources • Item runtime since previous maintenance on failed item
Preventive Maintenance
• Tasks carried out • Used maintenance time • Needed resources • Item runtime after previous maintenance • Failure behaviour since previous preventive maintenance

7.2 Operation and Maintenance (O&M) customers

In O&M service concept Outotec takes responsibility of operating and/or maintaining the customer owned equipment or full process plants with on-site staff. O&M contracts can be established as a part of a delivery of new equipment or plant, or for an older "brownfield" plant. These contracts span over longer time periods and therefore have increased ability to produce failure and maintenance data needed in RAM work.

Equipment failures and carried out maintenance tasks are recorded into enterprise asset management (EAM) software, from which they can be exported to external analysis tools. The exported data will include the complete maintenance history data of assets.

Due to workload management issues and steps taken to ensure that the reporting does not strain the operators and maintenance crews, the amount of failure modes used in reporting is narrowed down. Therefore data extracted from the O&M sites might not be able to answer the data needs of too sophisticated RAM models or analysis.

O&M site organizations carry out their own RAM projects after the site has been running long enough so that adequate amount of failure data has been accumulated. These RAM enhancement projects are handled by the personnel that have the best knowledge of the individual site and therefore the results are very site specific.

In addition to the RAM work at the site, data obtained from the O&M sites will most likely be the most comprehensive reliability data that the company can collect. As sites utilizing and O&M contract with Outotec are few in number, data is available on limited equipment inventory and operation environments. However, these sites can offer good and justifiable data on best practices and effectiveness of maintenance plans that can then be used as proof of concepts in development of other maintenance services and in marketing.

7.3 Remote Troubleshooting customers

Outotec offers remote troubleshooting support for some of its automation products. Failures or abnormal operation are diagnosed using a remote connection to the system and information acquired by interviewing the equipment operator. Based on acquired information Outotec service engineer gives suggestions on possible causes and remedies needed to restore the system to normal operating condition. On some products, the service engineer is able to remotely interact with the equipment to perform corrective actions himself.

Because the Outotec presentative is not present at the site, he or she cannot verify that the corrective actions taken are actually the same recommended. As the remote connection is available, he or she can confirm that the equipment has returned to the normal operating conditions, but as follow-ups are rare, presence of a hidden causes or failures cannot be determined. In some cases even determining the actual failure mode and cause remotely can be difficult.

Reliability data acquired from remote troubleshooting is very fragmented. Records consist of random failures on random equipment and only problems that the maintenance organization of the customer cannot solve are observed by the service organization.

However, troubleshooting cases might shed light on failure modes or causes that have not been identified before. This can be used both to advantage product design when designing next generation of product models, and in creating good service experiences for the customers by proactively taking contact with other customers with similar equipment and providing them with solutions to avoid the problem.

In the future, as sophisticated automation systems become more common, it may be possible to receive process data from non-automation products. This can enable remote failure mode, cause and effect identification on mechanical equipment.

7.4 Install base information

At the time of writing this thesis, the process of collecting and organizing installed base information was in its early stages at Outotec. First versions of customer site lists and equipment inventories were becoming available.

IBI database collects the customer equipment inventory. It can be used to find similar equipment used in similar applications and similar operational environment. In an ideal situation, the database offers a direct access to reliability data available from each customer. Even if this is not possible, at least it offers hints on which customers to use as a search parameter when accessing other information resources.

To increase the value of IBI database, it should include also design parameters used when designing the equipment during the manufacturing and delivery of the item and information on application and operation environment of the item. For older items in the install base these can be hard to come by but for new deliveries this information is available in the project documentation and should be added to IBI database when the item is added.

7.5 Expert opinion

When adequate field data are not available, expert opinion can be used instead. This is typically done by interviewing several experts who are seen to have deep enough knowledge about the studied device, process or technology.

As described on earlier chapters, most of the qualitative analysis relies heavily on technical experts and their knowledge on the analysed systems. Expert opinion can additionally be used also on quantifying the analysis.

Using expert opinion in analysis quantification has two clear disadvantages. Firstly, expert opinion is always objective and reflects only the experiences of an individual. Secondly, experts are usually reluctant to give numeric values for occurrence of different events. To counter these problems, methods (Purba;Lu;Zhang;& Pedrycz, 2013) (Mentes & Helvacioglu, 2011) (Ferdous;Khan;Sadiq;Amyotte;& Veitch, 2011) (Yang;Bonsall;& Wang, 2008) have been developed to use fuzzy algebra and logic to utilize linguistic expert opinion data together with statistical reliability data.

All of these methods are based on the realization that linguistic grading of probability (e.g. common/uncommon) includes a great degree of uncertainty. This is countered by using fuzzy algebra to transform the linguistic value options to probability ranges. Methods have varying ways to use weight coefficients to adjust the value of different experts based on their experience on the subject system.

Additionally some of the methods (Purba;Lu;Zhang;& Pedrycz, 2013) (Ferdous;Khan;Sadiq;Amyotte;& Veitch, 2011) go as far as turning the available reliability data and the used modelling structure (typically fault trees) to utilize fuzzy logic and algebra. This approach is used to account the facts that collected reliability data usually has some uncertainty in it and that fault tree analysis assumes basic events to be unrelated although they might not be.

Most of these fuzzy algebra logic methods are rather sophisticated and need analysts skilled in fuzzy algebra to be used.

7.6 Equipment manufacturer's data

Equipment providers can provide reliability data and maintenance recommendations for their equipment. However, these are typically constructed using generic presumptions about the final application and operational environment of equipment. These can vary greatly from the actual use of the equipment and should therefore be regarded with criticism. (Gulati, 2013)

One problem about reliability data provided by OEMs is that it is typically based only on information collected from the warranty period of the equipment. Therefore it contains only data obtain from customer complaints and does not give a representative picture about the end-life reliability. Because of these reasons, manufacturer data tends to be very optimistic. (Smith, 2011)

7.7 Commercial databases

There are several commercial databases that collect reliability data. These databases typically focus on certain industry or equipment type. During the writing of this thesis, the author could not access any commercial reliability database, so information provided here is based on literary references.

Smith (2011) describes that commercial data collection activities were in their peak in the 1980s, but declined in the 1990s after which most publications have not been updated. Databases can have great variance in failure rates depending on the source used. Therefore it is important to read through all additional notes provided about the source information used to produce the given rates.

7.8 Summary

It can be concluded from the presented data sources that the subject company has a wide variety of reliability data sources. However in most cases the accuracy of acquirable data is low.

For the data collection operations to be effective, the attention should be concentrated on sources where higher quality data can be obtained with lower investment. The sources with lower quality data should not be ignored as even single failure events can be valuable during such analysis as failure mode identification during FMEA.

In the next chapter field data collection is discusses and reporting models are developed.

8 Field data collection

The beginning of this chapter introduces the current state of the maintenance data collection in the subject company. The latter half of the chapter describes the development of a proposed model for the maintenance service event reporting.

8.1 Current state

At the time this thesis was written, the maintenance service offering and delivery capability of the subject company were still in development. Of the technologies that have service product management based in Finland, three thirds have localized service delivery capability in the local service centres around the world. However, all technology segments had geographical areas, where local capability was missing. Additionally some technologies, mainly ones with a smaller install base, were relying globally on small group of experts handling all operations.

On most technologies, the service event reporting was handled locally. Reporting was handled with either reporting forms produced by the local service centre or with forms modified from templates provided by global service product management. Data reported and the form it was reported varied greatly between service centres even within technologies. Use of free text descriptions about encountered failures, equipment condition and carried out tasks were very common.

Data storage was handled by filing the reports either locally in paper form or digitally in local databases. Global access to reports filed on paper was extremely hard as local employees had more pressing matters in their daily work than copying, scanning or transcribing old maintenance reports. Even access to digitally stored reports proved to be time consuming as getting in contact with local employees was difficult and handling data transfers to other parts of the organization was not considered a priority. In one case transferring data was found out to be impossible because the reports included personal information of the field service engineer responsible and local privacy legislation prohibited handing over this information to third parties.

8.2 Reporting

As described earlier, Outotec delivers several different types of maintenance services to its customers. These service deliveries are the main way to access installed base information for most of the equipment instances. To record this information, adequate reporting is a must. Due to differences in the maintenance types, information available from each maintenance type differs. Therefore a reporting system that can handle service-specific information is needed.

Additionally, the content of a single report is affected by the equipment type under observation. Therefore each equipment type needs a separate report for each service type.

To enhance the ability to gather installed base data, proposals for service-specific reporting templates were crafted. As the proprietary equipment product portfolio of the subject company is vast and includes several structurally and functionally distinct products, these proposals consider only the general level of collected information. Equipment specific details, such as defined failure modes and failure causes are not discussed. The content of service-specific reports is described in subchapters 8.4, 8.5, 8.6 and 8.7.

In addition to collecting maintenance data, maintenance reports act as a way to communicate performed work to the customer. Therefore reports must be easily transferred to the customer. However, as some information collected might be critical for the business model of the service provider, it should be possible to manually or automatically filter sensitive data form the customer copy.

In optimal situation reporting at the customer site would be conducted using an electronic reporting system that synchronises the reported data automatically to a centralized database. However, this will not be possible in quite some time and therefore paper reports or logbooks must be applied in field use. Using predetermined functional structures of equipment and possibilities offered by modern IT-solutions, the paper reports could be automatically generated before the customer visit to correspond with equipment to be maintained and tasks to be carried out.

8.3 Centralized database for maintenance reporting

To increase global availability of reliability data, the author recommends implementation of a centralized database for digital maintenance data.

The database should store all reliability data related to the install base acting as a data storage and offer easy access to all relevant parties through the organization. The database should offer search functionality so that data can be search and accessed by multiple parameters and cross-referenced between plants and customers. (EN-ISO 14224, 2006)

To the user, the database should offer and easily understandable logical structure that supports data application. On the administrative side, the system should be easily maintainable, for example new structures should be simple to create.

One of the key aspects of databases is the used architecture. As noted before, the subject company has multiple structurally and functionally differentiating products. Therefore the reporting database has to be able to support report structures that are equipment type and service type specific. Therefore it is the author's recommendation that object model database architecture is chosen.

In the object model, the software can be considered as a collection of objects. Objects are entities that can hold both data and procedures. Objects are defined by types called classes and they can have a hierarchy where a high level object class has subclasses. Object classes are defined in the program code, but objects themselves are created during the execution of the program code. (Mannan, 2012b)

Objects have a structure and an interface. The structure is fixed by the object class and can be based on aspects such as object type, its parent classes and so on. The interface is the visible part of the object that handles the communication with other objects. (Mannan, 2012b)

Challenges and requirements related to usability and data taxonomy are discussed in the Chapter 6.1.

8.4 Maintenance inspection

Maintenance inspection is a tool used to prepare for planning and execution of actual maintenance work. PSK Standards Association, a Finnish standardization organization for process industry, has defined the principles of maintenance inspection in its standard PSK 6202. As the inspection tasks carried out are highly dependent on the equipment type, the standard offers only a generic list on topics that should be included in the maintenance inspection report. This list was used as a basis for the proposal for a maintenance inspection report crafted in this thesis. It was further developed with several of technical service product managers of the subject company.

The content of the proposed maintenance inspection report can be found in Table 5.

Table 5: Content of maintenance inspection report

Maintenance Inspection report	
Topic	**Description**
1. General Information	**This chapter gives an overview on the scope of the inspection.**
Description of production process	Short description of the main process the inspected equipment is related to.
Content and objectives of inspection task	Description of the objectives of the inspection and tasks carried out to meet these objectives.
Work group	A list of personnel that participated on the inspection, disciplines represented and man-hours used.
2. Inspection summary	This chapter includes an overview of the inspection findings. Its objective is to highlight the aspects needing attention in the condition of inspected equipment.
General description of condition of objects	Short overall description on the condition of inspected equipment.
Objects demanding immediate repair	A list of items that are in such condition that they should be repaired as fast as possible. These items may cause danger for work safety, environment or reliability, availability and performance of the equipment.
Risks observed during inspection	A list of observed risks caused by the difference between observed condition and the original condition of the inspected equipment. These risks can be work safety related, environmental, operational and/or economical.
Inspection uncertainty and	Description of factors affecting the results of the

further observation	inspection and list of tasks which have to be considered in order to minimize the effect of those.
Actions and cost estimation	Recommendations for future maintenance actions and preliminary cost estimation for these actions.
3. Detailed Inspection results	
Functional parts of entities with condition classes	A list of inspected items and their condition grade, reasoning behind issued condition grading, used inspection method and additional observations.
Safety of inspection object	Detailed description of safety hazards discovered during inspection.
Energy economy of objects inspected	Estimation on the current state of the energy consumption of the inspected object compared with the design specifications.
Operating conditions	Comparison between the operation environment and operation procedures of the object in the current state and the design state.
4. Proposal for further examination	
Appendices	Pictures etc.

On the "Functional parts of entities with condition classes" section the condition of functional parts is described using condition classes. Standard PSK 6202 (2003) uses a four step grading system, presented in Table 6.

Table 6: Condition classes for equipment condition estimation

Grade	**Condition**
1	Excellent condition, good as new
2	Satisfactory condition, no immediate need for replacement or repairs
3	Adequate condition, need for replacement or repairs within a few years
4	Bad condition, must be repaired or replaced immediately

This grading should be printed on the inspection report within the "Functional parts of entities with condition classes" section to increase the readability of the report.

Some equipment may be subjected to such operating conditions, that their functional parts cannot be expected to last long periods even if the equipment is considered being in normal use. In these kinds of situations use of the previously presented condition grading is not reasonable. Grades should be adjusted to a more suitable form. It is extremely important to indicate the deviation from standard grading on the inspection report.

Additionally, the maintenance inspection could be used as an opportunity to check if the basic item information stored to the installed base about the inspected item is up-to-date. In this context, the author recommends that a thorough maintenance inspection should be carried out as part of ramp-up of any maintenance delivery contract.

From the reliability and availability analysis aspect maintenance inspections are not very lucrative information sources. Obtained information is fragmented as these inspections are carried out mostly with low frequency and at sites where actual maintenance actions are carried out by the customer or some other service provider.

8.5 Preventive and Predictive Maintenance

Preventive and predictive maintenance are both types of planned maintenance.

Standard EN 13306 defines preventive maintenance as "maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item."

The same standard defines predictive maintenance as: "condition base maintenance carried out following a forecast from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item."

Planned maintenance service deliveries of the subject company typically begin more as preventive maintenance, where maintenance scheduling is done using equipment-specific maintenance recommendations. Because these are based on typical operation conditions of the equipment, they can lead to maintenance schedules that cause over or under maintenance. Under maintenance causes equipment faults during operation periods, which causes unwanted down time, but also makes under maintenance easy to detect. Over maintenance on the other hand is hard to detect and causes hidden spare part and work costs that may be very hard to detect.

Preventive and predictive maintenance differ from each other mostly on planning and timing of maintenance execution. The actual work execution and included tasks are similar and can be reported using the same reporting template.

No mining industry specific standard on data collection from preventive maintenance could be found during the writing of this thesis. The closest attempt to standardize maintenance data collection is ISO 14224 that handles reliability data collection and exchange in oil and gas industry. The standard gives a very general classification to data that should be collected, but not in adequate depth to act as a base for collected data set.

For this thesis, a customized data set was formed with several of Outotec's technical services product managers. The data type classification follows the ISO 14224 standard, but the actual data types were selected by the writer and the group of experts. The proposed list for data to be collected is presented in Table 7.

Table 7: Proposed content of preventive and predictive maintenance report.

Data category / type	**Description**
Equipment data	
Equipment Identification code	Unique equipment code used to identify a single asset.
Maintenance Data	
Date and time	Starting and ending dates and times of the maintenance work.
Downtime caused	Total downtime that was caused by maintenance work.
Components maintained	A list of equipment components maintained.
Action taken per item	A list of maintenance actions carried out to each component.
Condition of equipment after maintenance work	A list of inspected items and their condition grade, reasoning behind issued condition grading, used inspection method and additional observations. Inspecting is done during preventive maintenance to help the planning of the next maintenance visit.
Work data	
Time used	Actual time used on each maintenance task.

Spare (and wear) parts used	A list of used spare parts. The list should include individual product codes, names and used amounts.
Materials used	A list of used materials. The list should include names, volumes and application of material.
Utility equipment used	A list of utility equipment that was used during the maintenance work.
Man-hours user per discipline	A list of needed workers per discipline and total working times used on the maintenance work.
Additional costs	A list of any additional costs not covered by work, spare-parts, materials, logistics or administrative costs.
Recommendations	
Spare parts to be ordered before next maintenance	Recommendations on what spare-parts are needed in stock on next preventive or predictive maintenance.

8.6 Corrective Maintenance

Standard EN 13306 defines corrective maintenance as "Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function."

On a service field that the subject company operates on corrective maintenance services are typically situations where the customer's maintenance organization needs troubleshooting help with OEM equipment of the subject company.

Like preventive and predictive maintenance, Standard ISO 14224 provides data categories to collect data on corrective maintenance. Proposal on collected data under these categories was crafted with technical service product managers of the subject company. The proposal is presented in Table 8.

Table 8: Proposed content of corrective maintenance report.

Data category / type	**Description**
Equipment data	
Equipment identification code	Unique equipment code used to identify a single asset.
Failure data	
Time and date of failure detection	The time the failure was detected by plant operators.
Failure detection method	Description of how failure was detected
Equipment use time at the	Amount of hours the equipment has been used when the

moment of failure	failure took place. Alternatively the time the failed component has been in use after the previous maintenance.
Failed component and accurate position	The name and accurate position of the failed component. Identification code, if applicable (e.g. spare-part)
Failure mode	The Manner in which the inability of an item to perform a required function occurs.
Caused damage	Possible damage caused to personnel, environment, facility or equipment itself by the failure.
Estimation of failure cause	Estimate for circumstances during the specification, design, manufacture, installation, use or maintenance that resulted in failure.
Maintenance Data	
Date and time	Starting and ending dates and times of the maintenance work.
Action taken	Corrective action taken to restore the equipment to the operating state.
Caused total downtime	Total downtime caused by the failure.
Work Data	
Time used	Time used on the actual maintenance work.
Used spare parts	A list of used spare parts. The list should include individual product codes, names and used amounts.
Used materials	A list of used materials. The list should include names, volumes and application of material.
Utility equipment used	A list of utility equipment that was used during the maintenance work.

8.7 Work Order approach

European standard EN 13460 (2009) takes a different approach to maintenance documentation. It introduces the work order, a document that is used through the whole maintenance delivery process. The standard defined work order as: "document containing all the information related to a maintenance operation and reference links to other documents needed to carry out the maintenance work."

As the definition implicates, the main purpose of the document itself is to plan the upcoming maintenance activity. However, the same data categories can be used when reporting realized maintenance actions, linking work reporting to the planning process.

Another noteworthy aspect of the work order is that it uses the same structure regardless of the maintenance type being reported. The categories are presented and described in Table 9

Table 9: Work order data categories.

Work Order information	Information description
W.O. and item identification	
W.O. number	Code assigned to a W.O. This code is unique to each W.O
W.O. Petitioner	Name of the authorized person requesting the maintenance service
Registration date	Date when the W.O. is issued.
Open date	Date when the W.O. is activated
Close date	Date when the W.O. is completed. Corresponding work finished.
Item code	Unique item identification code
Item location	Code corresponding to the geographical location of the item within the plant. Is normally attached to or part of the identification code.
Item running hours	A parameter used to record unit utilization.
Maintenance type information	
Type of maintenance	Code referring to the nature of maintenance activity.
Priority	Code to give information about the necessary precedence among the W.O.s for its activation. Priority has in some cases to do with criticality.
Safety and environmental regulations	Link to the possible safety and environmental requirements to perform the maintenance work, either mandatory or recommendations.
Retention justification	The reason why an open W.O. is not running at the moment. Downtime for each retention should also be included
Preventive maintenance information	
Frequency	Time between maintenance services within cyclic operations
Last operation time	Last date when a particular cyclic maintenance operation was performed
Resources estimation	Amount of the different resources intended to be used to accomplish the W.O. in a cyclic operation
Check list	Relation of points to inspect within a cyclic maintenance operation. Normally, these should be first line maintenance activities

Corrective maintenance information	
Complaint	Reason why a W.O. is issued. The symptom of the failure, normally detected by the user of the item.
Failing part	The malfunctioned component of the item. The repair or substitution of this part in addition to the description of the actuation is the solution of the problem.
Cause of failure	Estimation on circumstance resulting in the failure.
Technical procedure code	Link to technical documentation which holds the information about the right actuation way.
Actuation description	An explanation of the carried out operations.
Work information	
Labour amount	Working hours spent in carrying out the W.O; the sorts of hours: Normal, shift, night, extra, etc. should be specified.
Labour type	Personnel categories or skills of those who carried out the W.O.
Personnel	A list of all maintenance workers, who participated in carrying out the W.O.
Spare-part reference	A code list of all spare-parts used within the W.O.
Spare part amount	Number of each spare part type used within W.O.
External labour	List of external workers participated in carrying out the W.O.
External spare parts	Code list of all externally required spare parts used within the W.O.
Other external services	Service description, in the case of a contract with an external supplier of service for the W.O.
Acceptance	Maintenance work reception.

8.8 Selection of data structure to be used

The previously listed structures were compared to choose the most suitable one to be used in service delivery reporting. During the selection process data types recorded on each structure were reviewed, prioritized considering both value for internal use and value for customer and cross-referenced to other information sources. Additionally, the structures were compared with the list of data needs of different reliability analysis tools.

The work order format was found to be most applicable to use and was selected.

Next, the selected reporting structure was edited to make the structure lighter to use. This was done especially to support paper reporting that has to inevitably be used before transformation to fully electronic reporting can be achieved. During this process, some data categories were combined and some were removed. Data type periodization done in the reporting structure selection phase was used during the combining and removing of data categories. Additionally some new data types that were considered important but missing from the original structure were added.

Finally a data input form was assigned for each data type. The final reporting structure is illustrated in Table 10

Table 10: Final reporting structure

Work Order information	**Information description**	**Data input form**
Item identification		
Item code	Unique equipment identification code	Predefined, from install base
Customer modifications/ Technical specifications	Description of possible customer made modification or change in technical specification of the item	Free text field
Maintenance type information		
Type of maintenance	Code referring to the nature of maintenance activity	Selection from predefined list
Date and time	Starting and ending dates and times of the maintenance work.	Text input / selection
Downtime caused	Total downtime that was caused by maintenance work. (Should include the whole downtime, not only the actual maintenance time?)	Text input, hours
Safety and environmental regulations	Link to the possible safety and environmental requirements to perform the maintenance work, either mandatory or recommendations	Defined before dispatch

Preventive maintenance information		
Last operation time	Last date when a particular cyclic maintenance operation was performed	Text input / automatic input from database
Task list	A list of completed work per component. Includes the components and action taken. Additionally should include condition of components that are just checked.	Selected from predefined task categories (item -> task (->item condition) -> time used; item -> task -> time used ;…)
Actuation description	Explanation of the carried out operations.	Optional free text input
Corrective maintenance information		
Time of observation	Date and time when the failure was observed	Text input / selection
Item running hours	Parameter used to record unit utilization.	Text input
Failure effect	Description of how the failure affected the operation of the equipment	Predefined, free text for additional comments
Failing part	Malfunctioned component of the item. The repair or substitution of this part in addition to the description of the actuation is the solution of the problem.	Predefined in structural model
Failure mode	The symptom of the failure, normally detected by the user of the item.	Predefined (FMEA), text field for non-defined failures
Failure location	The exact position of the failure	
Failure cause	Circumstances that result in failure. (Assessment of the service engineer/technician)	Predefined, free text field for additional comments
Work information		
Labour amount	Working hours spent in carrying out the W.O; the sorts of hours: Normal, shift,	Free text, hours

	night, extra, etc. should be specified.	
Labour type	Personnel categories or skills of those who carried out the W.O.	Types free defined, amount input in free text, hours
Personnel	A list of all maintenance workers, who participated in carrying out the W.O.	Free text
Spare-part reference	Code list of all spare-parts used within the W.O.	Predefined, amounts as free text
Spare-part amount	Number of each spare-part type used within the W.O.	Selection from list predefined in structural model
Used materials		Free text
Used special tools		Free text
External labour	A list of external workers participated in carrying out the W.O.	Free text
External services	Service description, in the case of a contract with an external supplier of service for the W.O.	Free text
Other costs		Free text

9 Data Utilization

Different business units and processes can utilize installed base information in their decision making. Utilization is done through different analytics. As this thesis considers global markets of an OEM and service provider, these analytics are classified into three classes starting from local level and spreading through regional level to global level. This chapter introduces several possible analyses that could be used when adequate amount of data has been collected from the customer base. Most of the analytics are based on Ala-Risku's (2009) research, but modified to better suit the mining and metallurgy industry.

9.1 Local (customer) analysis

Local service centres can utilize installed base information to both resource and workflow management. For resource management, installed base information can be used to narrow down the probable causes for service requests and to estimate the needed resources and time for each service delivery. As the job requirements have been identified, service centres can tend to have field engineers with needed skill sets and adequate spare part items in stock, making dispatching more efficient and improving field service quality. (Ala-Risku, 2009)

To improve work flow management, installed base information can be used to analyse the state of customer equipment, ensure that dispatched personnel can reach the serviced equipment in minimal time and to minimize time used to find support on challenging service tasks. These actions can be used to improve and expedite decisions achieving high efficiency of the service delivery process. In addition to actions listed above, Ala-Risku (2009) mentions the possibility to optimize field engineer routes and minimize time used traveling. In the context of mining and metals industry this might not matter as much as the time required for the service work can be several days and the customer sites can be situated far from each other. Typically, the field engineer handles one site at the time and returns to the home office in between.

With these steps, the efficiency and effectiveness of service operations can be improved locally by maintaining and utilizing systematic installed base information.

9.2 Regional analysis

On a regional level, the installed base information can be used to support service resource planning by analysing competence and spare part inventories needed to carry out expected service deliveries in each area.

After analysing the expected service deliveries, the detailed service delivery reports on each service type can be analysed to see which kind of expertise and spare parts each service type requires. This information can then be used to manage both service centre field engineer competence and, local and regional spare part inventories to ensure service delivery capability, high field personnel productivity together with high spare part availability and high inventory turns. (Ala-Risku, 2009)

9.3 Global analysis

On the global level, installed base information can be used to support decision making in sales and product development. In this context product development includes both physical products and services.

Installed base information can be used to identify business opportunities with existing customers by analysing customer needs per product, service or application. Sales potential for upgrades can be identified from the customer application equipment inventory, item statuses and service histories. For new products, prospective markets can be identified using information on the customer equipment inventory by identifying complementary or substitutable products being used. Identifying performance and reliability requirements of specific context can be done by analysing customer equipment inventories, customer applications, item statuses and service histories. These results can further be used to understand market segments for new products. Ala-Risku (2009)

To achieve increased customer satisfaction with existing customers, installed base information can be used to support performance monitoring of quality control. When customizing sales offers, customer equipment inventories, customer site locations and service event histories can be used to identify relevant environmental and performance factors. These factors can be mapped to service configuration characteristics to produce sales offers that respond better to customer requirements. Customer equipment inventory and service event history can also be used to proactively search and correct problems, which can further increase customer satisfaction. Ala-Risku (2009)

The profitability of product-service system can be improved by evaluating customer contacts together with product and service performance. These analyses can be used to adjust pricing through segmentation or redesign products and services to lower after-sales costs. Customer equipment inventory and the service event record per product type can be used to evaluate service cost standards and to adjust customer prices to ensure profitable service offering. Equipment inventories together with application and environmental information can be used to evaluate appropriate use of equipment and compared to use indicated in customer orders. Produced results can be used to justify warranty costs. Customer equipment inventories and service event records per product type can also be used to find inadequate performance in service provider operations and therefore be used to increase the profitability of product types and service concepts. Ala-Risku (2009)

10 Conclusions

In the previous chapters, a concept for a structured data collection method and reporting models have been proposed. Additionally available data sources are introduced and requirements for electronic data collection platform and a global storage database are discussed.

During the conducted interviews and literary research it has become evident that reliability data from operational equipment is essential for planning maintenance and assessing maintenance performance as well as for development of service and physical products.

Additionally, information on average needs on several factors relating to maintenance of examined items are important when conducting life cycle cost estimations. These factors include downtime caused by maintenance, used spare parts, human resources and materials, and frequencies at which maintenance actions are carried out. Estimated and actuated life cycle costs can be used to justify why equipment and services provided by the subject company are good choices for the customer.

For a maintenance service provider, such as the subject company, the available information sources were found to be plentiful, but the information accuracy from these sources to be low. The company can collect information from multiple equipment individuals operating in various applications and environments. As a flip side, the accessible information relies to the provided service and the acquired information has high variance in specificity.

Although all available data is not suitable for all analysis need, most of it is still valuable in some context. Therefore effort should be invested in assuring that when data is collected, highest possible data quality is achieved.

The structured data collection method introduced in this thesis offers tools for developing and implementing service event reporting tools that counter these problems.

As the initial assignment was not limited to any one product, the method is rather generic.

In addition to development of internal data collection processes, steps should be made to forge cooperation with customer maintenance organizations to exchange maintenance information to supplement the data acquired from service suppliers' operations.

One significant factor affecting the quality of obtained data is the motivation of personnel participating to data collection. Poor usability of the data collection tools pays a significant role in reducing motivation. This makes usability a very important requirement for both electronic and manual data collection tools. Such things as predetermined failure modes, effects and causes can increase user convenience significantly.

However, predetermining data input values needs careful consideration, as both too few possibilities and overwhelming users with excessive amount of options are detrimental to the usability of an electronic reporting tool. Input options should be limited to most common ones and free text input field should be offered for infrequent failure types.

In addition to easily usable tools, data quality and field service engineer motivation can be increased by training and increasing involvement. Possible training subjects include use of available reporting tools, failure cause and effect identification and general mechanical training to the products the person is involved with. Additionally opportunities should be offered for field service engineers working with the same products to meet and exchange experiences.

Increasing involvement can be done by engaging experienced field service engineers to participate in reliability analysis work. This enforces the motivation to data collection by providing an impression that the collected data is actually used in the organization and therefore time used on reporting is not futile. In a longer time frame, possibilities to transfer some reliability analysis responsibilities to local service centres should be examined.

When data collection at the local level and data utilization at a global level reach a grade where they are considered being part of everyday routine, the acquired and available data can be utilized in even more sophisticated development of corporate performance. However, this requires significant investments in development of processes and tools together with building an accepting attitude inside the organization towards this important but easily overlooked activity.

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Appendix 1

Interviewee	Title
A	Product manager, technical services, Smelting
B	Product manager, technical services, Automation
C	Product manager, technical services, Filters
D	Product manager, technical services, Hydrometallurgy and Tankhouse Equipment
E	Product manager, technical services, Flotation
F	Product manager, technical services, Training
G	Plant reliability engineering manager